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An Investigation into Antimicrobial Production in the *Lactobacillus* Genus and the Fish Microbiome

A Thesis Presented to the National University of Ireland for the Degree of
Doctor of Philosophy

by

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Table of Contents

Declaration.....	i
List of Publications	ii
Abbreviations.....	iii
Abstract.....	v
Chapter 1: Antimicrobials from Lactic Acid Bacteria and their Potential Applications	1
Abstract	2
Introduction.....	3
Bacteriocins	4
Class I.....	6
Class II.....	8
Bacteriolysins (Formerly Class III Bacteriocins)	10
Bacteriocin Applications	11
Reutericyclin.....	19
Antimicrobial metabolites	20
Organic Acids.....	20
Reuterin.....	24
Hydrogen Peroxide	26
Ethanol.....	27
Diacetyl.....	28
Conclusion	28
References.....	34
Figures and Tables	31
Chapter 2: Formicin – A Novel Broad Spectrum Two-Component Lantibiotic Produced by <i>Bacillus paralicheniformis</i> APC 1576	34
Abstract	45
Introduction.....	46
Results	49
Isolation of <i>B. paralicheniformis</i> APC 1576	49
Identification of a Novel Two-Peptide Lantibiotic Operon.....	49
Bacteriocin Structure Prediction and Analysis	51
Homology between Bacteriocins.....	53
Discussion	54
Conclusion	57
Material and Methods.....	58
Isolation of bacteria from fish samples	58
Colony Mass Spectrometry	58

Draft Genome Sequencing	59
Bacteriocin Identification	59
Bacteriocin Purification	59
Antimicrobial Assays.....	60
Peptide Stability.....	60
References.....	67
Figures and Tables.....	62
Chapter 3: Bacteriocin Gene-Trait matching across the complete <i>Lactobacillus</i> Pan-genome.....	67
Abstract	70
Introduction.....	71
Results	73
Distribution of Bacteriocin Operons.....	73
Diversity of Bacteriocins Identified	74
Discussion	84
Materials and Methods	88
Bacteriocin Identification	88
Bacterial Strains.....	88
Bacteriocin Assays	88
Mass Spectrometry (MS)	89
Sodium Dodecyl Sulfate-Polyacrylamide Gel Electrophoresis (SDS-PAGE)	89
Bacteriocin Purification	90
References.....	92
Figures and Tables.....	92
Chapter 4: Reincarnation of Bacteriocins from the <i>Lactobacillus</i> Pangenomic Graveyard.....	123
Abstract	124
Introduction.....	125
Results	128
Identification of ‘Silent’ Pediocin Homologs	128
Heterologous Cloning	129
Production	129
Spectrum of Activity	130
Bacteriocin Structures	131
Discussion	133
Materials and Methods	138
Strains and Culture Conditions.....	138
Molecular Cloning and Gene Expression.....	138
Bacteriocin Assays	139
Bacteriocin Purification and Mass Spectrometry.....	140

References.....	148
Figures and Tables	141
Chapter 5: Life in Depth: the Resilient and Adaptive Nature of the Microbiome of Deep-Sea Fish. .	148
Abstract	151
Introduction.....	152
Results and Discussion	155
Compositional Analysis.....	155
Reconstruction of Metagenome-Assembled Genomes	160
Antibiotic Resistance	163
Natural Products.....	165
Bioluminescence.....	168
Conclusion	171
Material and Methods.....	173
Sample Collection and DNA Isolation	173
Whole-metagenome Shotgun Sequencing.....	173
Statistical Analysis	174
Composition	174
Reconstruction of Metagenome-assembled Bins	174
Antimicrobial Resistance	175
Natural products and Bioluminescence	175
References.....	176
Figures and Tables	176
Chapter 6: General Discussion	203
References.....	209
Acknowledgments	210

Declaration

I hereby certify that this material, which I submit for assessment on the programme of study leading to the award of Ph.D. is my own work along with the below contributions and has not been submitted for another degree, either at University College Cork or elsewhere.

Contributions:

Chapter 2: Ms. Paula O'Connor carried out mass spectrometry and peptide purification, Dr. Orla O'Sullivan carried out genome assembly.

Chapter 3: Ms. Paula O'Connor carried out mass spectrometry and peptide purification, Dr. Orla O'Sullivan carried bioinformatics analysis

Chapter 4: Ms. Paula O'Connor carried out mass spectrometry and peptide purification, Dr. Beatriz Mesa Pereira carried out vector design and heterologous expression in the *Lactobacillus* host.

Chapter 5: Dr. Calum Walsh carried out bioinformatics analysis

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List of Publications

Book Chapters

Collins, F.W., Rea, M.C., Hill, C. and Ross, R.P., 2019. *Lactic acid bacteria: microbiological and functional aspects*. CRC Press, 2019 (Accepted)

Research Papers

Collins, F.W., O'Connor, P.M., O'Sullivan, O., Rea, M.C., Hill, C. and Ross, R.P., 2016. Formicin—a novel broad-spectrum two-component lantibiotic produced by *Bacillus paralicheniformis* APC 1576. *Microbiology*, 162(9), pp.1662-1671.

Collins, F.W., O'Connor, P.M., O'Sullivan, O., Gómez-Sala, B., Rea, M.C., Hill, C. and Ross, R.P., 2017. Bacteriocin Gene-Trait matching across the complete *Lactobacillus* Pan-genome. *Scientific Reports*, 7(1), p.3481.

Collins, F.W., Mesa-Pereira, B., O'Connor, P.M., Rea, M.C., Hill, C. and Ross, R.P., 2018. Reincarnation of Bacteriocins From the *Lactobacillus* Pangenomic Graveyard. *Frontiers in microbiology*, 9.

Abbreviations

3-HPA	-	3-hydroxypropionaldehyde
CPM	-	Copies per Million
Dha	-	2,3-didehydroalanine
Dhb	-	2,3-didehydrobutyrine
DOM	-	Dissolved Organic Matter
EF-Tu	-	Elongation Factor Tu
GDHt	-	Adenosylcobalamin-dependent Glycerol Dehydratase
GRAS	-	Generally Regarded as Safe
HMM	-	Hidden Markov Model
IPTG	-	Isopropyl β -D-1-thiogalactopyranoside
LAB	-	Lactic Acid Bacteria
LAP	-	Linear azol(in)e-containing peptide
MAG	-	Metagenomic Assembled Genome
MALDI TOF	-	Matrix Assisted Laser Desorption/Ionization
MS	-	Mass Spectrometry
NRPS	-	Non-ribosomal Peptide Synthetase
PAGE	-	Polyacrylamide Gel Electrophoresis

PCoA	-	Principle Coordinate Analysis
PKS	-	Polyketide Synthase
POM	-	Particulate Organic Matter
RiPPs	-	Ribosomally Synthesised Post-translationally modified Peptides
SAM	-	S-adenosylmethionine
SDS	-	Sodium Dodecyl Sulfate
TMA	-	Trimethylamine
TOMM	-	Thiazole/oxazole-modified Microcin
WDA	-	Well Diffusion Assay

Abstract

This thesis outlines a study of the identification and characterisation of antimicrobials from two primary sources; the *Lactobacillus* genus and the microbiome of fish. Through the incorporation of a wide variety of techniques, this study successfully demonstrates how a variety of methods can be used for the identification and production of novel antimicrobials.

Chapter 1 gives an overview of the variety of different antimicrobials which can be produced by the lactic acid bacteria (LAB) which can play an important role in a number of processes, such as the preservation of fermented foods. These antimicrobials can vary from organic acids, such as lactic and acetic acid, to antimicrobial peptides known as ‘bacteriocins’.

Chapter 2 outlines the identification of a novel bacteriocin known as ‘formicin’ through traditional colony isolation and screening methods. Formicin was identified from *Bacillus paralicheniformis* APC1576, an antimicrobial producing strain isolated from the intestine of a fish. Using a combination of mass spectrometry and genomic screening, formicin was found to be a two-peptide lantibiotic, displaying antimicrobial activity against a broad range of Gram positive microbes.

In Chapter 3, through a combination of *in silico* and lab-based screening of the *Lactobacillus* pangenome, it was possible to determine the extent and diversity of bacteriocins encoded and produced by the genus. This study shows that bacteriocin production may not be as prevalent as previously believed, however of the bacteriocins which were identified from within the genomes, many were found to be novel. By screening the strains identified as harbouring bacteriocin-related genes, five novel active bacteriocins were identified.

Many strains of lactobacilli were found to encode bacteriocins, however upon analysis, these failed to display *in vitro* antimicrobial activity. Often the regulation of bacteriocin operons, or the loss of key bacteriocin-associated genes, results in the failure of these strains to produce bacteriocins when tested *in vitro*. Chapter 4 outlines a method for the heterologous expression of a

particular class of bacteriocins, the Class IIa 'pediocin-like' bacteriocins. Here, using an expression designed for Class IIa bacteriocins, it was possible to produce eight novel bacteriocins identified from genomic data.

In Chapter 5 shotgun metagenomic sequencing is used to characterise the compositional and functional properties of the intestinal microbiome of deep sea fish. Here it can be seen how bacteria have adapted to live in this environment by encoding systems to relieve the stress associated with life at higher pressures. The study also outlines the diversity of the potential antimicrobials which may be produced within the microbiome of such fish whilst also highlighting an apparent lack of genes associated with known mechanisms of antibiotic resistance.

Overall, the results of this work demonstrate the effectiveness of a variety of methods for identifying novel antimicrobials from a range of bacterial sources.

Chapter 1: Antimicrobials from Lactic Acid Bacteria and their Potential Applications

Book Chapter: Lactic Acid Bacteria: Microbiological and Functional Aspects, Fifth
Edition 2019 (Accepted)

Abstract

The antimicrobial activity of lactic acid bacteria (LAB) has been utilised throughout recent human history. The fermentation of foods is an ancient method of preservation and often relies on the production of antimicrobials from bacteria such as LAB to inhibit the growth of spoilage microbes and pathogenic strains. Such antimicrobials include bacteriocins, organic acids, hydrogen peroxide and ethanol; these can be particularly useful for industrial use due to their potent activity and low toxicity. As consumers move away from the use of synthetic preservatives and food treatments, bacteriocins and organic acids represent obvious natural alternatives for food preservation. Similarly in the medical field where antibiotic resistant superbugs are becoming an increasing concern, antimicrobials from LAB represent potentially novel treatments for infections where classical antibiotics may no longer be effective in the future. This chapter will outline the different antimicrobials produced by LAB and discuss their potential applications in the food processing and medical industries.

Introduction

Lactic acid bacteria (LAB) are a non-sporulating group of Gram-positive bacteria found in environments ranging from food to the GI tract. LAB have been utilised for millennia due to their ability to preserve food and are key to the production of many fermented foods such as yoghurt, cheese, sourdough bread, fermented vegetables such as sauerkraut and fermented meats. The metabolites produced by the LAB from the breakdown of the original substrate (i.e. milk, meat or vegetable carbohydrates and proteins) both may alter the properties of the product whilst potentially inhibiting the growth of competing spoilage microbes (Ross et al., 2002). A range of antimicrobial metabolites can be produced by LAB (Figure 1), primarily in the form of organic acids such as lactic acid, which acidifies the product thus inhibiting the growth of competing microbes (Pérez-Díaz et al., 2013). Many LAB have also been shown to produce antimicrobial peptides known as bacteriocins which target and kill sensitive competing microbes .

The World Health Organization (WHO) estimated that 600 million food-borne illnesses occurred in 2010, leading to an estimated 420,000 deaths (World Health Organization (2015)). The implementation of systems to improve food safety is of high importance. Antimicrobials produced by LAB have been shown to inhibit a wide range of food spoilage bacteria and the addition of bacteriocins such as nisin to food can effectively reduce the levels of pathogens in a variety of products (O'Sullivan et al., 2002).

Another major issue is the escalating crisis of antimicrobial resistant pathogens, already a cause of an estimated 700,000 deaths per year, a figure predicted to rise to 10 million deaths per year by 2050 (O'Neill, 2014). Coupled with this is a paucity of new antibiotics to target such pathogens (World Health Organization, 2017). The antimicrobials produced by

LAB show potential for applications in the medical sector, with many shown to effectively inhibit multi-drug resistant strains (Okuda et al., 2013). Whilst much research has focused on the use of these antimicrobials in food, further work needs to be done to realise their potential in medicine (Cotter et al., 2013). This chapter reviews the range of antimicrobials produced by LAB, outlining their potential applications in industrial and medical settings.

Bacteriocins

Bacteriocins are heat stable antimicrobial peptides produced by bacterial cells and, unlike traditional antibiotics, are gene-encoded and ribosomally synthesised. The antimicrobial spectrum of these bacteriocins can vary, ranging from broad spectrum targeting a wide range of bacterial species to narrow spectrum inhibiting only closely related bacterial species. LAB are recognised as prominent bacteriocin producers (Zacharof and Lovitt, 2012). Whilst a wide variety of bacteriocins exist, a common genetic architecture is found in many of the associated gene clusters. The structural gene in bacteriocin operons encodes the active peptide, this usually contains an N-terminal leader sequence with important functions during bacteriocin production. When translated within the cell the leader sequence reduces or abolishes the antimicrobial activity of the bacteriocin, preventing the cell from being killed by its own antimicrobial. In certain bacteriocins the leader can also be recognized by modification enzymes which can then direct the post translational modification of the active bacteriocin peptide. The leader is also crucial for bacteriocin secretion whereby dedicated ATP-binding cassette (ABC) bacteriocin transporters recognize the leader sequence and cleave it at a specific motif (i.e Gly-Gly) as it is being exported from the cell, thus releasing an active bacteriocin (Oman and van der Donk, 2010). Bacteriocins generally have their own secretion system encoded within the

operon, which can consist of single or multiple ABC transporters. These transporters also often include protease domains for cleavage of the bacteriocin signal sequence (Havarstein et al., 1995). Some bacteriocin have been shown to be secreted via the Sec translocase system (Herranz and Driessen, 2005). Bacteriocin operons also encode genes encoding immunity proteins which prevent the strains being killed by their own bacteriocins (Draper et al., 2012). Bacteriocin production can also be under tight regulation in producer cells due to the presence of a two component regulatory system within the operon which has an important role in quorum sensing (Rohde and Quadri, 2006, van der Ploeg, 2005). Certain bacteriocins also have key genes encoding modification and accessory proteins; however the presence of these depends on the class of bacteriocin.

LAB produce a wide variety of different bacteriocins which can be grouped into classes based on their structure, genetics and mode of action (Table 1). Many classification systems for bacteriocins have been proposed, but we will follow the system outlined by Cotter *et al.* as this has probably been the most used classification system in recent years (Cotter et al., 2013).

Class I

Class I bacteriocins undergo enzymatic post translational modification. Such modifications have important structural and functional roles for these bacteriocins. Class I bacteriocins can be further broken down into subclasses based on how the peptides are modified. For this chapter we will only discuss the classes which contain LAB derived bacteriocins.

Lantibiotics

The lantibiotics are the largest group of modified bacteriocins, and are produced by a range of LAB. These bacteriocins are termed lantibiotics due to the presence of lanthionine and methyllanthionine bridges within the peptides. Serine and threonine residues can be dehydrated to form 2,3-didehydroalanine (Dha) and (Z)-2,3-didehydrobutyrine (Dhb). Dha and Dhb can then react with the thiol group on cysteine residues within the peptide, forming internal thioether crosslinks known as lanthionine and methyllanthionine bridges, respectively (Willey and van der Donk, 2007). These dehydration and cyclisation reactions are catalysed by modification enzymes encoded within the bacteriocin operon. These modifications can be carried out by two separate enzymes (LanB and LanC) in type 1 lantibiotics, or a single enzyme (LanM) in type 2 lantibiotics (Marsh et al., 2010). Type 3 and 4 lantibiotics also exist but these are much less common.

Nisin is a type I lantibiotic produced by strains of *Lactococcus lactis* and represents one of the more well-known and commercialised bacteriocins. Nisin is a 34 amino acid lantibiotic, containing 5 (methyl)lanthionine ring structures along with three dehydrated residues (two Dha and one Dhb) (Hooven et al., 1996). Nisin interacts with lipid II in sensitive cells where the globular N-terminus binds to a pyrophosphate moiety in lipid II. Once bound

the linear C-terminal tail of nisin inserts into the bacterial membrane which results in the formation of a pore complex. This pore causes leakage of cytoplasmic material from the bacterial cell which leads to cell death (‘t Hart et al., 2015).

TOMMs

The thiazole/oxazole-modified microcins (TOMMs) are another member of the class I post-translationally modified bacteriocins. TOMMs all contain heterocycles derived from cysteine, serine, and threonine residues (Cox et al., 2015). Linear azol(in)e-containing peptides (LAPs) are a group of TOMMs produced by LAB. Streptolysin S from *Streptococcus pyogenes* is one such LAP however, unlike typical bacteriocins, it is a potent cytolytic toxin and virulence factor. Streptolysin modification is carried out by a complex of three key enzymes encoded within the operon. SagC is a cyclodehydratase which then removes hydrogens from these modified amino acids resulting in the formation of thiazoline, oxazoline and methyloxazoline rings. SagB is a dehydrogenase which converts the thiazoline and (methyl)-oxazoline residues into thiazole, oxazole and methyloxazole heterocycles, respectively. SagC is a cyclodehydratase which then removes hydrogens from these modified amino acids resulting in the formation of thiazoline, oxazoline and methyloxazoline rings. A third protein, SagD, aids in the formation of the SagBCD complex (Lee et al., 2008). Despite a lack of characterised LAPs from other LAB, operons have been found in some *Lactobacillus*, *Lactococcus* and *Oenococcus* strains (Collins et al., 2017, Alvarez-Sieiro et al., 2016).

Thiopeptides are another family of TOMM bacteriocins, in addition to azoline and azole residues these can also contain Dha and Dhb residues due to the dehydration of Ser and Thr residues by LanB-like enzymes encoded within the thiopeptide operon (Zhang and Liu,

2013). In a recent *in silico* screen of the human microbiome metagenomic data a novel thiopeptide called 'lactocillin' was identified and characterised from a *Lb. gasseri* strain. This is active against a range of pathogens and represents a potential novel antimicrobial compound for the treatment of vaginal infections (Donia et al., 2014).

Glycocins

The glycocins are a family of post-translationally modified bacteriocins characterised by the glycosylation of amino acid residues on the peptide. The glycocins are a relatively small family of bacteriocins; however several have been isolated from LAB. Glycocin F is a 43 amino acid bacteriocin produced by *Lb. plantarum* KW30 (Norris and Patchett, 2016) and is one of the more studied of these bacteriocins. It is composed of two α -helices held together by two disulphide bonds followed by a C-terminal tail. The peptide contains two β -linked N-acetylglucosamine moieties attached to the oxygen and sulphur residues on Ser18 and Cys43 respectively, this S-glycosylation on the Cys residue is very rare (Venugopal et al., 2011, Brimble et al., 2015).

Class II

Class II bacteriocins differ from class I in the fact they do not undergo extensive post-translational modification. These bacteriocins are further classified based on their composition and structure.

Class IIa

The class IIa or 'pediocin-like' bacteriocins are single unmodified peptides with characteristic anti-listerial activity. These bacteriocins all contain a highly conserved N-terminal YGNGV motif often followed by a Cys residue involved in the formation of a

disulphide bridge, the peptides contain a less conserved hydrophobic C-terminus. An accessory protein encoded within the bacteriocin operon ensures correct disulphide bond formation and peptide folding (Oppegard et al., 2015). These peptides work by initially binding to the cell using the extracellular loop of the mannose phosphotransferase sugar uptake system as a receptor (Kjos et al., 2010). Once bound to the cell, the more hydrophobic C-terminus penetrates the cell membrane where it then forms a pore complex, thus causing leakage from the cell and eventual cell death (Papagianni and Anastasiadou, 2009).

Class IIb

The class IIb bacteriocins are two-peptide unmodified bacteriocins where both peptides are generally required in equal amounts for optimum antimicrobial activity. These bacteriocins are typically encoded by adjacent genes in the bacteriocin operon.(Nissen-Meyer et al., 2011). Despite being composed of two quite different peptides, these bacteriocins interact to act as a single antimicrobial entity. Most of these two-peptide bacteriocins contain GxxxG motifs which are involved in helix-helix interactions; this may allow the two peptides to interact and form a single functional unit (Fimland et al., 2008, Nissen-Meyer et al., 2010). These permeabilize the membrane of sensitive target cells to small molecules which results in cell death (Nissen-Meyer et al., 2010). Many of the class IIb bacteriocins which have been identified are produced by LAB, and appear to be the most prevalent type of bacteriocins encoded by lactobacilli (Collins et al., 2017)

Class IIc

Class IIc bacteriocins are circular peptides, linked by N-terminal to C-terminal covalent bonds (Cotter et al., 2005). The circularised structure aids in the pH and thermal stability of

these peptides and helps confer resistance to proteolytic enzymes. These bacteriocins act by inducing ion permeation in the membrane of sensitive cells resulting in a loss in membrane potential and cell death (Hemu et al., 2016, Gálvez et al., 1991). Many of the class IIc bacteriocins which have been discovered are produced by LAB. The mechanism of peptide circularisation is still unclear and the enzymes involved have yet to be identified.

Class IId

The class IId bacteriocins are a group of single peptide, non-pediocin like bacteriocins. They bear no homology to pediocin-like bacteriocins and are not modified, acting as a heterogeneous group of peptides which don't fit in other classes. Many diverse bacteriocins from LAB are found within this class. Bactofencin is one such bacteriocin, it is a small unmodified cationic bacteriocin produced by *Lb. salivarius* DPC6502 (O'Shea et al., 2013). One interesting subgroup of these bacteriocins is a group displaying homology to the bacteriocin lactococcin 972. Lactococcin 972 is bacteriocin produced by *Lc. lactis* subsp. *lactis* IPLA 972 and acts as a homodimer. This is a growing group of bacteriocins, several of which are encoded by LAB, with a unique mode of action and may warrant separate classification in the future (Collins et al., 2017, Letzel et al., 2014).

Bacteriolysins (Formerly Class III Bacteriocins)

Bacteriolysins are large heat sensitive antimicrobial proteins and due to their size and structure these proteins they are no longer considered bacteriocins. Several such peptides have been shown to be produced by LAB, such as enterolysin A (Nilsen et al., 2003), zoocin A (Heath et al., 2004), millericin B (Beukes et al., 2000) and helveticin J (Joerger and Klaenhammer, 1990). Bacteriolysins work by degrading the cell wall of sensitive cells. The N-terminus of these proteins contains a catalytic domain homologous to those of cell wall

degrading enzymes, the C-terminus then contains a potential cell wall binding domain (Nilsen et al., 2003, Heath et al., 2004).

Bacteriocin Applications

The antimicrobial activity of bacteriocins coupled with their low toxicity makes them attractive compounds for industry and the fact that they are naturally produced by GRAS organisms may also render them more acceptable to health conscious consumers. A limited number of bacteriocins are already in use in the food industry such as nisin (Younes et al., 2017) and carnocyclin A which is marketed as Micocin® (Liu et al., 2014). However, the potential exists to widen the scope of applications, particularly as antimicrobials in the medical field (Cotter et al., 2013). Indeed, research into bacteriocin applications is increasing: the granting of bacteriocin-related patents increased by 66% between 2010-2015 compared to the previous five years, covering a range of applications from biomedical research to nanotechnology (López-Cuellar et al., 2016).

Food Preservation and Safety

The use of bacteriocins in the food industry has primarily focused on food biopreservation and safety. Bacteriocins offer a natural alternative to the addition of chemical preservatives to food and have been shown to improve the flavour of certain fermented foods (Younes et al., 2017, O'Sullivan et al., 2002). Due to the peptide nature of bacteriocins they are generally digested in the gut upon ingestion, thus eliminating potential downstream effects on the microbiota as compared to traditional antibiotics (Umu et al., 2017).

Bacteriocins themselves are used in food manufacture in at least three ways (Figure 2), the first of which is the addition of partially purified bacteriocins to the food product (Chikindas et al., 2018). Nisaplin® (Danisco), a dried powder containing 1.82% nisin is one such product (Gough et al., 2017). Nisin was awarded generally regarded as safe (GRAS) status by the FDA in 1988 and has been approved by the World Health Organization as a food additive and was also assigned the E number E234 (Younes et al., 2017). Nisin is one of the most commonly used bacteriocin food preservatives, its broad spectrum of activity, heat stability and history of effectiveness making it an attractive option for the food industry. The addition of Nisaplin® to cottage cheese was shown to effectively control levels of *Listeria monocytogenes* (Ferreira and Lund, 1996). Nisaplin® was also shown to immediately reduce *L. monocytogenes* levels by 3 log CFU/g in queso fresco, a non-fermented cheese (Lourenço et al., 2017).

The second method by which bacteriocins may be added to food is as crude fermentates containing the active bacteriocins. One such example is ALTA® 2351 (Kerry Bioscience) a pediocin containing fermentate which has been shown to reduce *L. monocytogenes* numbers in raw sausage batter over 60 days (Knipe and Rust, 2009). Another popular example is microGARD™ (Danisco), a product of the fermentation of skimmed milk by LAB. This is extensively used in industry and has been shown to inhibit the spoilage of dairy products such as cottage cheese and yoghurt (Makhal et al., 2015, Salih et al., 1990).

The third approach is to use bacteriocin-producing strains as starter or protective cultures in fermented foods. One advantage of this is that *in situ* production of bacteriocins by starter cultures reduces the need for the addition of external preservatives. The use of bacteriocin producing cultures has been shown to be effective in the biopreservation of a

variety of foods such as fish (Gómez-Sala et al., 2016), meat (Díaz-Ruiz et al., 2012), vegetables (Settanni and Corsetti, 2008) and dairy products (Mills et al., 2017). One such example is the use of the nisin producer *Lc. lactis* subsp. *lactis* IFO12007 in the production of miso, a fermented soybean paste. The strain was used as a starter culture and was shown to inhibit the growth of *Bacillus subtilis*, even when this spoilage bacteria is inoculated at a concentration of 10^6 cells/g (Kato et al., 1999). The combination of a nisin and lactacin 3147 producing *Lc. lactis* strain with a plantaricin producing *Lb. plantarum* strain served as a protective culture in cheese production causing a reduction of *Listeria* numbers to 0.3 log CFU/g compared to 2.9 log CFU/g in the non-bacteriocin producing control (Mills et al., 2017). This study highlighted how bacteriocin-producing cultures can be used to stack bacteriocins in a food system thus creating multiple antimicrobial hurdles.

Bacteriocins are useful as part of a hurdle technology in combination with other methods for food preservation (Hsiao et al., 2016). The use of other compounds and treatments together with the addition of bacteriocins may also lead to synergistic antimicrobial activity. Organic acids for example can help increase the net charge of bacteriocins at low pH, thus aiding in bacteriocin translocation through the cell wall. This potential interaction is particularly useful in LAB which often produce these acids and bacteriocins concurrently (Mills et al., 2011). The role of organic acids as antimicrobials will be discussed later in this chapter. The use of outer membrane permeabilizing agents such as EDTA can also extend the range of activity of these bacteriocins to include Gram-negative bacteria such as *E. coli* O157:H7 in food (Ananou et al., 2005). The combination of lactacin 3147 and the lactoperoxidase system in powdered infant formula, for example, was shown

to inhibit the growth of pathogenic *Cronobacter* species up to 12 hours after rehydration of the milk formula (Oshima et al., 2012).

Packaging and materials

Another potential use for bacteriocins is their incorporation into packaging and other materials such as nanofibers. In cases where food comes into contact with the antimicrobial packaging, bacteriocins diffuse from the packaging thus inhibiting the growth of surface microorganisms. The antimicrobial packaging thus serves as an extra hurdle in food processing to improve safety, prevent food spoilage and extend product shelf life. The incorporation of bacteriocins into packaging can have advantages over direct bacteriocin addition to food through the reduction of non-specific binding of the bacteriocins to food components rather than the targeted bacterial strains, and by reducing the risk of bacteriocin degradation and inactivation in the food matrix (Laridi et al., 2003).

There are several ways in which bacteriocins can be incorporated into such materials. Bacteriocins can be simply coated or absorbed onto a polymer or incorporated directly into the polymer matrix for packaging (Deshmukh and Thorat, 2013). Numerous studies on a range of foods have shown the effectiveness of nisin incorporated into food packaging (Irkin and Esmer, 2015). For example, the use of packaging containing immobilised nisin was shown to reduce *Listeria innocua* and *Staphylococcus aureus* levels as well as those of other microbes in sliced cheese and ham in modified atmosphere packaging, thus improving shelf life (Scannell et al., 2000).

Bacteriocin producing strains as probiotics

Probiotics are defined as live microorganisms, which when consumed in adequate amounts, confer a health benefit on the host (Pineiro and Stanton, 2007). Bacteriocin production can be considered an important probiotic trait due to the potential of such strains to inhibit pathogenic bacteria in the GI tract (Dobson et al., 2012). An example of this was demonstrated by Corr *et al.* who showed that the bacteriocin-producing *Lactobacillus salivarius* UCC118 strain displayed the ability to protect mice against infection with *L. monocytogenes* whilst a non-bacteriocin-producing mutant failed to show the same effect (Corr et al., 2007). Millette *et al.* also demonstrated that the nisin Z producing *Lc. lactis* MM19 and pediocin PA-1 producing *P. acidilactici* MM33 reduced vancomycin-resistant enterococci (VRE) in infected mice (Millette et al., 2008). Bacteriocins may also help strains establish themselves in a complex environment by helping them out-compete the resident microbiota in a particular niche (Dobson et al., 2012). The production of the bacteriocins blpMN by *Str. pneumoniae* was shown to aid the establishment of the strain in the mouse nasopharynx (Dawid et al., 2007). The administration of an *E. faecalis* strain harbouring the bacteriocin 21 encoding plasmid pPD1 was able to colonize and outcompete VRE lacking pPD-1 in infected mice, thus indicating the role bacteriocin production may play in the establishment producing strains in the host (Kommineni et al., 2015). Bacteriocins may also act as useful signalling peptides between the bacteria themselves and also with the host. The production of plantaricins by *Lb. plantarum* WCFS1 for example was shown to be linked to a change in the levels of the cytokines interleukin 10 and 12 from peripheral blood mononuclear cells which may offer protection against colitis (van Hemert et al., 2010, Foligne et al., 2007). The benefits of bacteriocin production in probiotic LAB however is influenced by the producers ability to actively establish itself and produce bacteriocins in the host, a trait which is not always guaranteed. The pediocin PA-1 producing strain *P.*

acidilactici UL5 for example failed to establish itself in the mouse intestinal microbiota as the strain was not detectable in faecal samples two days after administration. This *Pediococcus* strain was originally isolated from fermented sausage and therefore may simply not have been well adapted to survive and establish in the GI tract of the host (Dabour et al., 2009).

Medical applications of bacteriocins

With the increasing prevalence of antibiotic resistant pathogens, bacteriocins represent a potential novel treatment for the control of these pathogens due to their potency and low toxicity. Much of the work which has been done in this field has involved the use of animal models, thus more clinical human research must be completed to determine the actual efficacy of bacteriocins in clinical applications. Nonetheless, the results of trials using model systems are promising. Intravenous injections of nisin, for example, was shown to be more effective than vancomycin treatment in *Str. pneumoniae* infected mouse models (Goldstein et al., 1998). Due to its inhibitory activity against *Helicobacter pylori* nisin can be used in the treatment of peptic ulcers and has been commercialized for treatments of gastric *Helicobacter* infections (Dicks et al., 2011). The stability and activity of nisin at low pH makes this a potentially useful antimicrobial for the treatment of this gut pathogen. The narrow spectrum of inhibition of pediocin-like bacteriocins could also be useful in the treatment of listeriosis which is extremely dangerous to pregnant women and immunocompromised individuals. Intra-gastric administration of pediocin PA-1 in mice was shown to reduce *Listeria* levels and slow pathogen translocation to other organs whilst having no effect on the intestinal microbiota (Dabour et al., 2009).

Bacteriocins can also be used in oral and respiratory health, for example a nisin-containing mouthwash was found to reduce gingivitis in beagle dogs (Howell et al., 1993). Nisin F was also shown to be effective against *S. aureus* infections in the respiratory tracts of immunosuppressed rats, a remedy which could be beneficial in the treatment of respiratory diseases in immunocompromised and cystic fibrosis patients (De Kwaadsteniet et al., 2009). Bacteriocins also have potentially useful roles in skin care by modulating the skin microbiome and inhibiting pathogens. The bacteriocins ESL5 produced by *E. faecalis* SL-5 displayed antimicrobial activity against *Propionibacterium acnes*, a key factor in the pathogenesis of acne vulgaris. The incorporation of the concentrated bacteriocin into a topical lotion was shown to significantly reduce inflammatory lesions in treated patients in comparison to a placebo (Kang et al., 2009).

One of the issues associated with the use of bacteriocins in medical applications is that they can be degraded proteolytically in the body, thus reducing their effectiveness (Rink et al., 2010). Encapsulation of the bacteriocins and the use of drug delivery systems may circumvent this, allowing bacteriocins to be delivered directly to the area of interest in the host (Leserman et al., 1980). Encapsulation of bacteriocins may allow for their slow and extended release resulting in prolonged antimicrobial activity whilst also protecting the peptide from degradation in the body (Langer and Folkman, 1976).

A similar concept can be used in a clinical setting and the incorporation of bacteriocins into nanofibers and materials has numerous potential uses. Electrospinning is one such method whereby bacteriocins such as nisin can be incorporated into the core of nanofibres. The use of such nisin-eluting nanofibres in wound dressings has been shown to significantly reduce the bacterial load of *S. aureus*-induced skin infections of a wound in a murine model.

This represents a potentially useful medical barrier against the acquisition of skin infections (Heunis et al., 2013). The incorporation of these antimicrobials into dressings and fibres extends the potential use of bacteriocins in the medical field.

Veterinary applications of bacteriocins

Bacteriocins also display potentially useful benefits for animal care. One such application is the use of bacteriocins to treat mastitis in lactating animals. Mastitis is the inflammation of the mammary gland as a result of the infection with pathogenic microbes. A study by Cao *et al.* used an intramammary infusion of nisin to treat mastitis in dairy cows; the results for the nisin treatment had a clinical cure rate similar to that of gentamycin treatment. Nisin, however, is a food grade product with very few associated issues if it enters the food chain, as opposed to antibiotics such as gentamycin (Cao et al., 2007). A nisin based teat sealer was shown to reduce *S. aureus* and *E. coli* levels by 3.9 log and 4.22 log respectively after a one-minute exposure to the formula, a result comparable to conventional chemical treatments. The nisin formula however displayed a lower potential for skin irritation in comparison to the chemical treatments (Sears et al., 1992). A lacticin 3147 containing fermentate was used as a teat dip for mastitis prevention in dairy cows. Here teats were first coated with a pathogen before being treated with the teat dip for ten minutes, the lacticin 3147 containing fermentate was shown to reduce *Staphylococcus*, *Str. dysgalactiae* and *Str. uberis* levels by 80%, 97% and 90% respectively (Klostermann et al., 2010).

The antimicrobial activity of bacteriocins may also be useful for the treatment of GI tract infections in a range of animals. A bacteriocin OR-7 from *Lb. salivarius* was shown to reduce the colonization of chickens by *Campylobacter jejuni*. The purified bacteriocin was encapsulated and incorporated into chicken feed, chicks were then challenged with *Campylobacter jejuni* strains. Bacteriocin treatment was shown to greatly reduce pathogen colonization (Stern et al., 2006). An *in vitro* model of swine intestinal fermentations displayed the potential of pediocin A to inhibit the growth of pathogenic clostridia in the intestine, again representing an alternative to the use of traditional antibiotics in animal husbandry (Casadei et al., 2009).

Bacteriocins also represent an alternative to the addition of subclinical levels of antibiotics to animal feed as growth promoters. Dietary nisin was shown to increase feed conversion and body weight gain in broiler chickens. While the exact mechanism of action is unclear, nisin was shown to modulate the gut microbial ecology, thus the authors postulated that it may be a result of improved nutrient absorption and utilization or due to an improved immune response to pathogenic *Eimeria* parasites (Józefiak et al., 2013). Similarly the addition of pediocin A to the feed of chickens challenged with *Clostridium perfringens* improved their growth and feed conversion rates (Grilli et al., 2009).

Reutericyclin

Reutericyclin is an antimicrobial *N*-acylated tetrameric acid produced by a number of *Lb. reuteri* strains (Gänzle, 2004). Reutericyclin is produced by the combined activity of a non-ribosomal peptide synthetase (NRPS) and polyketide synthase (PKS) encoded within the *Lb. reuteri* genome. It is unique in the fact that is one of the very few functional NRPS/PKS systems described in LAB (Lin et al., 2015). Reutericyclin acts as a proton-ionophore and

dissipates the transmembrane ΔpH of sensitive cells by translocating protons across the cytoplasmic membrane (Gänzle, 2004). It is active against a range of Gram-positive bacteria including pathogens such as *Clostridium difficile* and MRSA (Cherian et al., 2014).

Reutericyclin producing *Lb. reuteri* strains have a number of potential uses in both food production and as potential probiotics due to the antimicrobial activity of the compound. Reutericyclin production in sourdough has been shown to help *Lb. reuteri* persist in the environment and remains active against sensitive strains in the dough (Gänzle and Vogel, 2003). This suggests that such producing strains may have potential as starter cultures for food preservation (Gänzle and Vogel, 2003). As a potential probiotic trait, a reutericyclin producing strain was found to subtly alter the fecal microbiota of weanling pigs, however no effect on clostridial toxins in host faeces was observed after treatment (Yang et al., 2015).

Antimicrobial metabolites

In certain cases, metabolic waste products and intermediates produced by LAB during fermentation can themselves display antimicrobial activity. These antimicrobial metabolites can play an important role in food preservation by limiting the growth of spoilage and pathogenic microbes (Ross et al., 2002). The composition and characteristics of these antimicrobials will be further discussed below.

Organic Acids

Organic acids are a by-product of LAB metabolism, however in several cases these have been shown to possess antimicrobial activity. The primary acids produced by LAB are lactic acid and acetic acid, however others such as formic acid can also be produced (Lindgren and Dobrogosz, 1990). Their antimicrobial activity may be primarily due to the lowering of the

internal pH of sensitive cells. In the uncharged form these acids are lipid permeable and thus can freely diffuse into the cell's cytoplasm (Hirshfield et al., 2003). Once in the cytoplasm they can dissociate causing an accumulation of anions, lowering the cells internal pH (pHi) (Salmond et al., 1984). This can affect numerous processes in the cells and can lead to internal enzyme denaturation. The increased anion concentration within the cell can also lead to an increase in the transportation of potassium ions into the cell (Roe et al., 2002). This influx of ions increases the turgor pressure within the cell, and in order to balance this, glutamate is then transported out of the cells which results in the disruption of the cells' osmolarity and thus inhibits cell growth (Warnecke and Gill, 2005). A drop in pH can also induce changes in the fatty acid composition of the cells membrane (Cotter and Hill, 2003). The inhibition of cells by weak acids is not however solely due to lowering the cells pHi, as different acids can have specific effects on cells; for instance the treatment of *E. coli* cells with formate or acetate leads to distinctive transcriptional responses between the two acids. Acetate was shown to induce the production of proteins found in the RpoS regulon which is an important controller of the bacterial stress response, while formate caused reduced steady state expression of these genes (Kirkpatrick et al., 2001). Acetic, lactic and citric acids were also shown to display different levels of antimicrobial activity against *L. monocytogenes* even when cells had identical pHi values (Young and Foegeding, 1993). Such differences may be explained by the distinctive anion pools within the cells after treatments with each acid, the particular lipophilicity of each acid may also affect cells differently as was shown in yeast cells (Hirshfield et al., 2003, Capozzi et al., 2009).

Lactic acid is the primary organic acid produced by LAB and, as with other organic acids, its activity is not solely due to the lowering of the cells pHi (Mols and Abee, 2011). Upon

exposure to lactic acid, *Bacillus cereus* displayed an altered expression of 196 genes which are not associated with the general response to acidic shock, again indicating a more specific mode of action for this molecule. Rather, it was shown to alter the metabolism of these cells by controlling the expression of genes involved in amino acid metabolism (Mols et al., 2010). In addition lactic acid may also induce oxidative stress within cells (Mols et al., 2010, Mols and Abee, 2011, Abbott et al., 2009).

Acetic acid was also found to have a large impact on gene expression in *Bacillus cereus*, altering the regulation of 1430 genes, affecting a variety of pathways involved in oligopeptide and amino acid transport and metabolism which is similar to the response seen for lactic acid. Acetic acid also altered carbohydrate transport and metabolism in cells, with genes involved in glucose, fructose, lichenan and trehalose transport and metabolism being down-regulated (Mols et al., 2010). As with lactic acid, acetic acid may also inhibit cells by causing oxidative stress (Mols et al., 2010, Mols and Abee, 2011)

Applications

Organic acids can be used in a variety of applications, and due to their broad spectrum of activity and their 'generally regarded as safe' (GRAS) status they are particularly suited to the food industry (Chai et al., 2016). Solutions containing organic acids are used in the meat processing industry in the US and Canada for carcass decontamination (Loretz et al., 2011). They may also be added to juices and beverages where they can serve as biopreservatives and as acidity regulators (Quitmann et al., 2013). The neutralization of these organic acids can produce salts which are useful due to their wide spectrum of activity against a range of pathogens and food spoilage microbes such as *E. coli* O157, MRSA and *Pseudomonas aeruginosa* (Lee et al., 2002, McWilliam Leitch and Stewart, 2002). The sodium salts of these

organic acids in particular can be used to improve the shelf life of products such as meat, poultry and fish and to control the growth of pathogens (Sallam, 2007, Maca et al., 1997). Levels up to 4.8% by weight of formulation of sodium and potassium lactate are permitted in food to inhibit microbes (Juneja and Thippareddi, 2004). These may also be useful if incorporated into food packaging whereby a controlled release may prolong a product's shelf life by inhibiting spoilage microorganisms (Wang et al., 2015). Often these salts may have benefits beyond their antimicrobial activity, sodium lactate for example can also act as a humectant and emulsifier (Brewer et al., 1991). Organic acids may also be highly useful in animal feed systems as reducing the microbial load of feedstuffs there is an increase in nutrients available to the host. The production of these acids may also reduce the production of ammonia by spoilage microbes and also reduce the pH of the digesta (Dibner and Buttin, 2002).

The combination of treatment with organic acids and other compounds can greatly enhance the antimicrobial activity of both and can lead to potential novel treatments for food preservation. The combination of lactic acid with the phenolic compound carvacrol has been shown to have synergistic antimicrobial activity against *Shigella sonnei* in infected lettuce leaves (Chai et al., 2016). The combination of organic acids and transition metals was also found to be highly synergistic with an up to a 1000 fold increase in antimicrobial activity whilst greatly also improving the effective range of activity against many pathogenic bacteria. Here the organic acids form complexes with these transition metals, increasing the permeability of the metals which leads to an increase in their intracellular concentration. The addition of organic acids to copper sprays currently used in plant and crop treatment could thus greatly increase their antimicrobial potency (Zhitnitsky et al., 2017). Synergistic

antimicrobial activity between different organic acids and UV-A radiation has also been reported even when used at sub-lethal levels (de Oliveira et al., 2017).

The production of these acids by LAB is in itself an important commercial trait for food fermentations. It is the production of lactic acid and other organic acids which helps in the preservation of fermented foods (Leroy and De Vuyst, 2004). While acids have important functional roles in the fermentation of many products (i.e. separation of curds and whey in cheese manufacture), these acids also reduce the growth of spoilage microbes by lowering the pH of the food to a prohibitive level. LAB are involved in the fermentation of a wide range of food, such as fermented meats (salami), fermented vegetables (kimchi, sauerkraut) and fermented dairy products (kefir, yoghurt). Thus, fermentation by LAB provides a cheap and cost effective method for food preservation whilst also often enhancing flavour and nutritional qualities (Ezeji and Ojimekwe, 1993).

Reuterin

Reuterin is an antimicrobial compound which is an intermediate in the metabolism of glycerol in certain species. The name is derived from its most notable producer, *Lb. reuteri*, however several other *Lactobacillus* species have also been shown to produce this compound, as well as cells from other genera such as certain strains of *Klebsiella* (Martin et al., 2005, Sauvageot et al., 2000, Schütz and Radler, 1984, Slininger et al., 1983). Reuterin is composed of a mixture of 3-hydroxypropionaldehyde (3-HPA), its dimer and its hydrated form (Vollenweider and Lacroix, 2004). 3-HPA is an intermediate in the breakdown of glycerol to 1, 3-propanediol. Glycerol is first converted to 3-HPA by the adenosylcobalamin-dependent glycerol dehydratase (GDHt), 3-HPA can then be further broken down into 1, 3-propanediol by an NAD⁺-dependant oxidoreductase (Liu and Yu, 2015). *Lb. reuteri* is a

particularly useful producer of reuterin due to its ability to tolerate larger concentrations of the compound compared to other producing species (Vollenweider and Lacroix, 2004). Reuterin inhibits sensitive cells by inducing oxidative stress as the reactive aldehyde in reuterin reacts with thiol groups of small molecules and proteins which can lead to their inactivation (Schaefer et al., 2010). Reuterin has a broad spectrum of activity, inhibiting a wide range of both Gram-positive and Gram-negative bacteria along with yeasts, moulds and protozoa (Cleusix et al., 2007).

Applications

Due to its broad spectrum of activity, reuterin may potentially be a useful antimicrobial. Reuterin treated mice infected with *Trypanosoma brucei brucei* displayed a 61% reduction in parasitemia levels and had an increased survival rate after a 7 day treatment (Yunmbam and Roberts, 1993). Due to its low potential toxicity in the body along with its inhibitory spectrum against food borne pathogens and spoilage bacteria, reuterin could also be used in combination with other treatments as a potential food preservative (Fernández-Cruz et al., 2016). When added to a Spanish curdled milk product reuterin alone displayed little antimicrobial activity against *L. monocytogenes* or *S. aureus*, however when used together with nisin and the lactoperoxidase system there was synergistic inhibition of these pathogens (Arqués et al., 2008). Reuterin-producing *Lb. reuteri* strains may also serve as potential probiotics. *Lb. reuteri* itself has been shown to survive gastric transit and has the ability to colonise the intestine (Vollenweider and Lacroix, 2004). Models of the colonic epithelium have shown that reuterin production improves the protection offered by *Lb. reuteri* against the adherence, invasion and intracellular survival of *Salmonella enterica* serovar Typhimurium in a model system (De Weirdt et al., 2012). The availability of

glycerol in the human intestine remains unclear, however, a *Lb. reuteri* strain was shown to produce reuterin in the gut of gnotobiotic mice following a cecal glycerol injection (Morita et al., 2008).

Hydrogen Peroxide

Several LAB have also been found to produce hydrogen peroxide in the presence of oxygen (Hertzberger et al., 2014, Schellenberg et al., 2012, Hütt et al., 2016). The exact mode of action for the antimicrobial activity of H_2O_2 is not completely understood; however it is most likely a combination of DNA damage, protein oxidation and membrane disruption of the target cell (Tamarit et al., 1998, Imlay et al., 1988). This can be due to the production of reactive hydroxyl radicals formed by Fenton's reaction (Linley et al., 2012). These hydroxyl radicals cause breaks in DNA due to their reaction with the methyl groups of thymine (Engevik and Versalovic, 2017, Di Mascio et al., 1989). The small molecular size of the molecule allows it to easily enter the cells where it can react with internal proteins and DNA, the activity of H_2O_2 can also be affected by whether the compound is in liquid or gaseous form (Finnegan et al., 2010). H_2O_2 is thought to be more effective against Gram-positive than Gram-negative bacteria and anaerobic strains are thought to be more sensitive to the compound as they lack the peroxidases and catalases encoded by aerobic bacteria which allows them to break down H_2O_2 (McDonnell and Russell, 1999). The activity of H_2O_2 can also be enhanced synergistically by acting together with the lactic acid produced by these bacteria (Atassi and Servin, 2010). Here, the membrane damage induced by lactic acid may make cells more susceptible and sensitive to the activity of H_2O_2 (Engevik and Versalovic, 2017).

Applications

The antimicrobial activity associated with H₂O₂ production makes it a potentially useful probiotic trait and its importance can be especially seen in the vaginal microbiota. H₂O₂ producing lactobacilli have been associated with protection against the acquisition of bacterial vaginosis and their absence is associated with a greater risk of acquiring HIV-1 infection (Hawes et al., 1996, Martin Jr et al., 1999). H₂O₂ production may also support colonization of the vagina by producing strains (Vallor et al., 2001). Whilst H₂O₂ production has been associated with colonisation, it has been shown that the levels produced by such strains may not be sufficient to inhibit the growth of vaginal pathogens and that lactic acid may be playing a greater antimicrobial role (O'Hanlon et al., 2010, O'Hanlon et al., 2011, Gong et al., 2014). Rather than acting as an antimicrobial H₂O₂ may have a more important immunomodulatory role in the vagina, lowering the levels of pro-inflammatory cytokines. This may explain the positive correlation between H₂O₂ producing lactobacilli and reduced bacterial vaginosis levels (Mitchell et al., 2015).

Ethanol

Ethanol is another antimicrobial product resulting from the metabolic reactions of certain LAB. Alcohols such as ethanol are commonly used as disinfectants due to their broad spectrum of activity, inhibiting bacterial cells, fungi and viruses. Ethanol is thought to damage cell membranes and denature proteins which disrupts crucial cell processes (McDonnell and Russell, 1999). Whilst ethanol at high concentrations displays potent antimicrobial activity, the levels produced by cells *in vivo* are unlikely to reach high enough concentrations to act as an effective antimicrobial (Sissons et al., 1996, Elshagabee et al., 2016). Despite this, ethanol produced by LAB can display additive or synergistic effects when

combined with other antimicrobial such as lactic acid which is also produced by these strains (Oh and Marshall, 1993).

Diacetyl

Diacetyl is a metabolic product from LAB which has also been shown to display antimicrobial activity. Diacetyl is an alternative minor product of the metabolism of some of these strains and can be formed by the spontaneous oxidation of acetolactate, an intermediate in the conversion of pyruvate to acetoin (Gänzle, 2015, Cocaign-Bousquet et al., 1996). The formation of diacetyl by LAB can be beneficial for fermented foods and other products due to its butter-like aroma, diacetyl has also been found to display antimicrobial activity against a range of bacteria. Whilst its activity is not as strong as other antimicrobials (Olasupo et al., 2003), it can inhibit the growth of Gram-negative bacteria which are typically unaffected by bacteriocins from LAB such as pediocin PA-1 or nisin (Kang and Fung, 1999, Gao et al., 1999). Gram positive strains tend to be less sensitive to diacetyl activity (Lanciotti et al., 2003). The concentration of diacetyl which is normally found in fermented foods is much lower than that required for antimicrobial activity and is unlikely to play a large role in bacterial inhibition in the environment (Clark and Winter, 2015, Helander et al., 1997). Continued exposure to diacetyl in an industrial setting has also been associated with lung disease which makes the molecule less attractive as an additive (Clark and Winter, 2015, Harber et al., 2006)

Conclusion

Antimicrobials produced by LAB could potentially represent an untapped resource in regards to food processing and medical applications. With increasing concerns over food safety and the increase of multidrug resistant superbugs there is an urgent need for novel treatments. In this respect, bacteriocins, in particular, offer much potential. Many studies have focused on nisin, outlining its efficacy against important pathogens; it is also approved as a food additive and is extensively used in certain food processing industries. As we have seen, LAB produce a plethora of bacteriocins with potential to follow the same route as nisin for food safety and medicinal applications.

Another advantage of bacteriocins, over other antimicrobials, is that they can be easily altered through genetic manipulation owing to their gene-encoded nature (Field et al., 2015). Modification of the nisin peptide for example has already led to the identification of mutants with enhanced antimicrobial activity (Healy et al., 2013). This may allow scientists to overcome some of the deficiencies associated with bacteriocins such as their degradation and stability in food matrices and the body. The narrow spectrum of activity of certain bacteriocins also allows pathogens to be targeted more directly with less collateral damage to the rest of the microbiota (Rea et al., 2010).

Whilst production of purified antimicrobial compounds from LAB could prove to be economically unfeasible, LAB themselves serve as antimicrobial micro-factories, producing a range of antimicrobial compounds *in situ*. This feature of LAB is particularly suited to their role as starter cultures in food fermentations and as probiotics in the realms of host health.

To date, much of the research into bacteriocins and other antimicrobials from LAB has focused on the food industry but the antibiotic resistance crisis has placed an urgent need on the development of novel antimicrobials. Furthermore, our knowledge of the

importance of our microbiota clearly indicates that such therapies must impart minimal damage to the host's microbiota. In this regard, LAB antimicrobials offer a potential option in the development of narrow-spectrum antimicrobial compounds which impart their pathogen-inhibiting effects with minimal consequences for the mammalian host.

Future research should now focus on expanding the LAB antimicrobial repository beyond the handful which have made it into the commercial and medical realms with an emphasis on progressing these molecules towards intelligently-designed studies which provide evidence of their safety and efficacy in practical situations and towards clinical and field trials for their debut into the domain of evidence-based medicine.

Figures and Tables

Figure 1. LAB produce a variety of antimicrobials which can inhibit and kill sensitive microbes. Compounds such as lactic acid and diacetyl are metabolic waste products which can also act as antimicrobials. Bacteriocins are antimicrobial peptides which may be produced by LAB to target and inhibit competing bacteria.

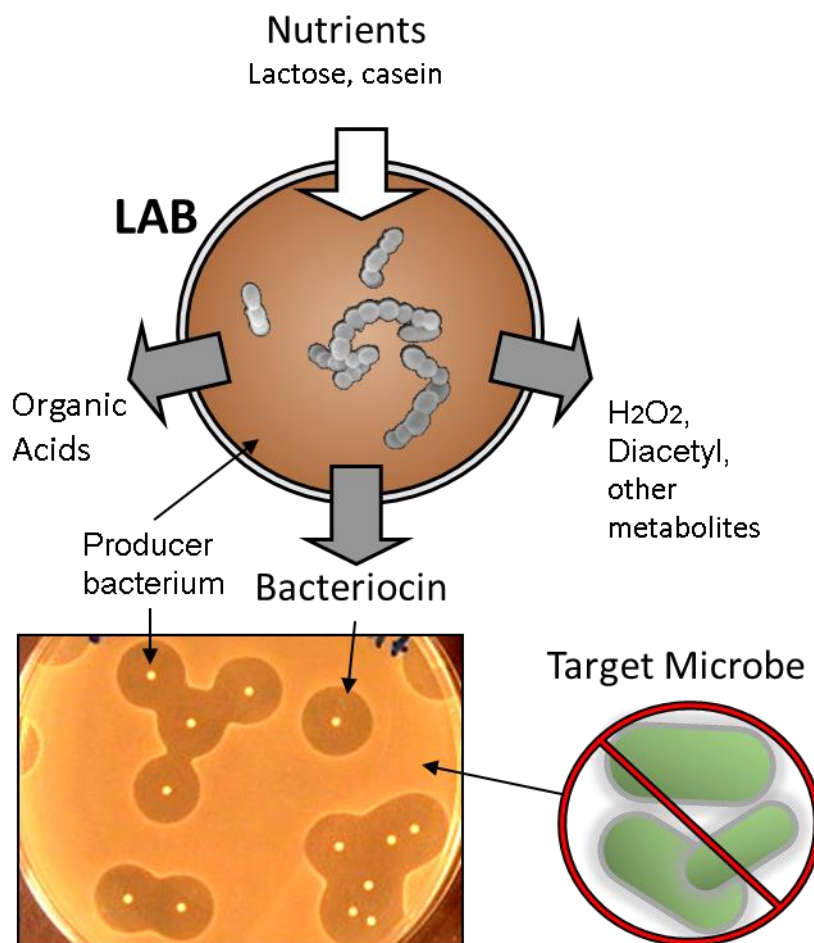


Figure 2. LAB can be utilised in food biopreservatoin in several ways. (a) LAB can be used as starter cultures in the production of fermented foods, whereby the *in situ* production of bacteriocins and other antimicrobials inhibits the growth of spoilage microbes. (b) Bacteriocins from LAB cultures can also be concentrated into purified and semi-purified food additives for use as preservatives in the food processing industry.

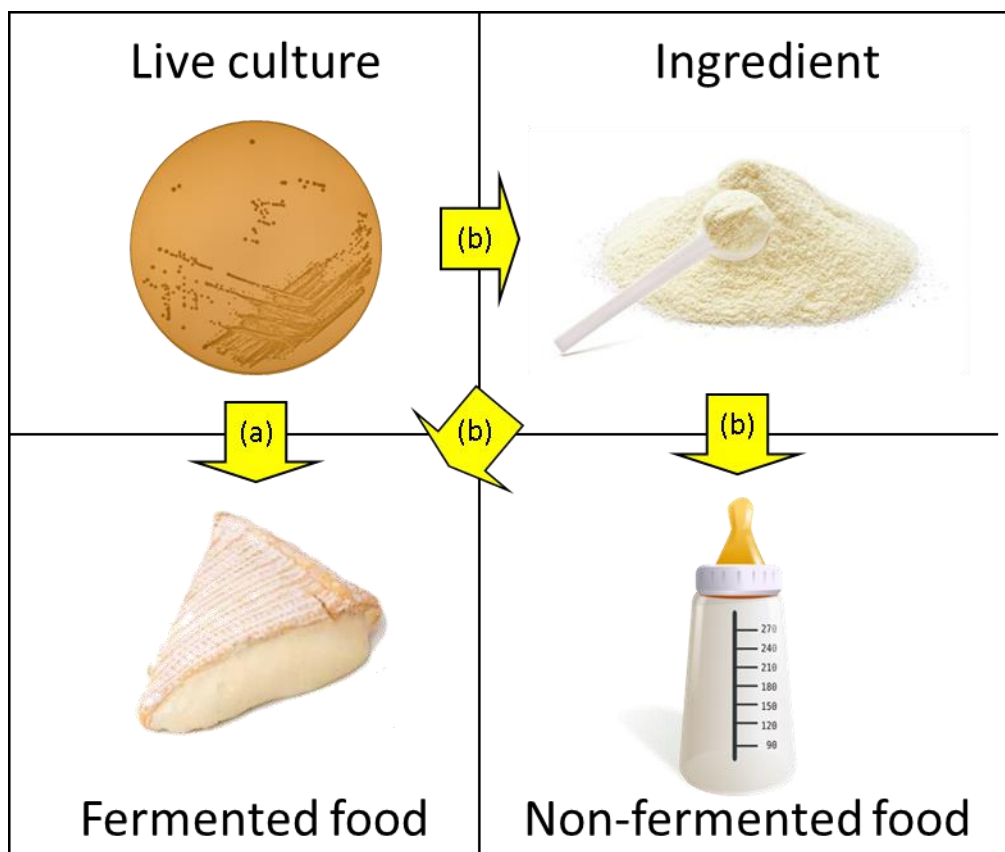


Table 1. Notable bacteriocins produced by LAB

Class I	Producer	Notable Targets	Reference
Lantibiotics			
Nisin	<i>Lc. lactis</i> subsp. <i>lactis</i>	<i>L. monocytogenes</i> , <i>S. aureus</i> , <i>Str. pyogenes</i>	(Rogers and Whittier, 1928)
Mutacin B-Ny266	<i>Str. mutans</i> Ny266	<i>Enterococcus</i> sp., <i>Staphylococcus</i> sp., <i>Propionibacterium acnes</i>	(Mota-Meira et al., 1997)
Lacticin 3147	<i>Lactococcus lactis</i> DPC3147	<i>L. monocytogenes</i> , <i>E. faecalis</i> , <i>S. aureus</i>	(Ryan et al., 1996)
TOMM			
Streptolysin	<i>Str. pyogenes</i>	Erythrocytes, leukocytes, platelets	(Todd, 1938)
Lactocillin	<i>Lb. gasseri</i> JV-V03	<i>Gardnerella vaginalis</i> , <i>Corynebacterium aurimucosum</i> , <i>E. faecalis</i>	(Donia et al., 2014)
Glycocins			
Glycocin F	<i>Lb. plantarum</i> KW30	<i>Enterococcus</i> sp., <i>Streptococcus</i> sp., <i>Bacillus</i> sp.	(Kelly et al., 1996)
Class II			
Class IIa			
Pediocin PA-1	<i>P. acidilactici</i> PAC-1.0	<i>L. monocytogenes</i> , <i>Lactobacillus</i> sp., <i>Clostridium tyrobutyricum</i>	(Henderson et al., 1992)
Enterocin A	<i>E. faecium</i> CTC492	<i>L. monocytogenes</i> , <i>E. faecalis</i> , <i>Cl. tyrobutyricum</i>	(Aymerich et al., 1996)
Class IIb			
ABP-118	<i>Lb. salivarius</i> subsp. <i>salivarius</i> UCC118	<i>Bacillus coagulans</i> , <i>L. monocytogenes</i> , <i>L. innocua</i>	(Flynn et al., 2002)
Plantaricin S	<i>Lb. plantarum</i> LPCO10	<i>Propionibacterium</i> sp., <i>Cl. tyrobutyricum</i> , <i>E. faecalis</i>	(Jimenez-Diaz et al., 1993)
Class IIc			
Carnocyclin A	<i>Carnobacterium maltaromaticum</i> UAL307	<i>S. aureus</i> , <i>L. monocytogenes</i> , <i>E. faecalis</i>	(Martin-Visscher et al., 2008)
Acidocin B	<i>Lb. acidophilus</i> M46	<i>L. monocytogenes</i> , <i>Cl. sporogenes</i> , <i>Brochothrix thermosphacta</i>	(Leer et al., 1995)
Class IId			
Bactofencin A	<i>Lb. salivarius</i> DPC6502	<i>S. aureus</i> , <i>L. monocytogenes</i>	(O'Shea et al., 2013)
Lactococcin 972	<i>Lactococcus lactis</i> subsp. <i>lactis</i> IPLA 972	<i>Lactococcus</i> sp., <i>Lb sake</i>	(Martinez et al., 1996)

References

- 'T HART, P., OPPEDIJK, S. F., BREUKINK, E. & MARTIN, N. I. 2015. New insights into nisin's antibacterial mechanism revealed by binding studies with synthetic lipid II analogues. *Biochemistry*, 55, 232-237.
- ABBOTT, D. A., SUIR, E., DUONG, G.-H., DE HULSTER, E., PRONK, J. T. & VAN MARIS, A. J. 2009. Catalase overexpression reduces lactic acid-induced oxidative stress in *Saccharomyces cerevisiae*. *Applied and environmental microbiology*, 75, 2320-2325.
- ALVAREZ-SIEIRO, P., MONTALBAN-LOPEZ, M., MU, D. & KUIPERS, O. P. 2016. Bacteriocins of lactic acid bacteria: extending the family. *Appl Microbiol Biotechnol*, 100.
- ANANOU, S., GÁLVEZ, A., MARTÍNEZ-BUENO, M., MAQUEDA, M. & VALDIVIA, E. 2005. Synergistic effect of enterocin AS-48 in combination with outer membrane permeabilizing treatments against *Escherichia coli* O157: H7. *Journal of Applied Microbiology*, 99, 1364-1372.
- ARQUÉS, J., RODRÍGUEZ, E., NUÑEZ, M. & MEDINA, M. 2008. Antimicrobial activity of nisin, reuterin, and the lactoperoxidase system on *Listeria monocytogenes* and *Staphylococcus aureus* in cuajada, a semisolid dairy product manufactured in Spain. *Journal of dairy science*, 91, 70-75.
- ATASSI, F. & SERVIN, A. L. 2010. Individual and co-operative roles of lactic acid and hydrogen peroxide in the killing activity of enteric strain *Lactobacillus johnsonii* NCC933 and vaginal strain *Lactobacillus gasseri* KS120. 1 against enteric, uropathogenic and vaginosis-associated pathogens. *FEMS microbiology letters*, 304, 29-38.
- AYMERICH, T., HOLO, H., HÅVARSTEIN, L. S., HUGAS, M., GARRIGA, M. & NES, I. F. 1996. Biochemical and genetic characterization of enterocin A from *Enterococcus faecium*, a new antilisterial bacteriocin in the pediocin family of bacteriocins. *Applied and Environmental Microbiology*, 62, 1676-1682.
- BEUKES, M., BIERBAUM, G., SAHL, H. G. & HASTINGS, J. W. 2000. Purification and partial characterization of a murein hydrolase, millericin B, produced by *Streptococcus milleri* NMSCC 061. *Appl Environ Microbiol*, 66, 23-8.
- BREWER, M. S., MCKEITH, F., MARTIN, S. E., DALLMIER, A. W. & MEYER, J. 1991. Sodium Lactate Effects on Shelf-Life, Sensory, and Physical Characteristics of Fresh Pork Sausage. *Journal of Food Science*, 56, 1176-1178.
- BRIMBLE, M. A., EDWARDS, P. J., HARRIS, P. W., NORRIS, G. E., PATCHETT, M. L., WRIGHT, T. H., YANG, S. H. & CARLEY, S. E. 2015. Synthesis of the Antimicrobial S-Linked Glycopeptide, Glycocin F. *Chemistry-A European Journal*, 21, 3556-3561.
- CAO, L., WU, J., XIE, F., HU, S. & MO, Y. 2007. Efficacy of nisin in treatment of clinical mastitis in lactating dairy cows. *Journal of dairy science*, 90, 3980-3985.
- CAPOZZI, V., FIOCCO, D., AMODIO, M. L., GALLONE, A. & SPANO, G. 2009. Bacterial stressors in minimally processed food. *Int J Mol Sci*, 10, 3076-105.
- CASADEI, G., GRILLI, E. & PIVA, A. 2009. Pediocin A modulates intestinal microflora metabolism in swine in vitro intestinal fermentations. *Journal of animal science*, 87, 2020-2028.
- CHAI, C., LEE, S., KIM, J. & OH, S. W. 2016. Synergistic Antimicrobial Effects of Organic Acids in Combination with Carvacrol Against *Shigella Sonnei*. *Journal of Food Safety*, 36, 360-366.
- CHERIAN, P. T., WU, X., MADDOX, M. M., SINGH, A. P., LEE, R. E. & HURDLE, J. G. 2014. Chemical modulation of the biological activity of reutericyclin: a membrane-active antibiotic from *Lactobacillus reuteri*. *Scientific reports*, 4.
- CHIKINDAS, M. L., WEEKS, R., DRIDER, D., CHISTYAKOV, V. A. & DICKS, L. M. 2018. Functions and emerging applications of bacteriocins. *Current opinion in biotechnology*, 49, 23-28.
- CLARK, S. & WINTER, C. K. 2015. Diacetyl in foods: a review of safety and sensory characteristics. *Comprehensive Reviews in Food Science and Food Safety*, 14, 634-643.
- CLEUSIX, V., LACROIX, C., VOLLENWEIDER, S., DUBOUX, M. & LE BLAY, G. 2007. Inhibitory activity spectrum of reuterin produced by *Lactobacillus reuteri* against intestinal bacteria. *BMC microbiology*, 7, 101.

- COCAIGN-BOUSQUET, M., GARRIGUES, C., LOUBIERE, P. & LINDLEY, N. D. 1996. Physiology of pyruvate metabolism in *Lactococcus lactis*. *Antonie van Leeuwenhoek*, 70, 253-267.
- COLLINS, F. W., O'CONNOR, P. M., O'SULLIVAN, O., GÓMEZ-SALA, B., REA, M. C., HILL, C. & ROSS, R. P. 2017. Bacteriocin Gene-Trait matching across the complete *Lactobacillus* Pan-genome. *Scientific reports*, 7, 3481.
- CORR, S. C., LI, Y., RIEDEL, C. U., O'TOOLE, P. W., HILL, C. & GAHAN, C. G. 2007. Bacteriocin production as a mechanism for the antiinfective activity of *Lactobacillus salivarius* UCC118. *Proc Natl Acad Sci U S A*, 104, 7617-21.
- COTTER, P. D. & HILL, C. 2003. Surviving the acid test: responses of gram-positive bacteria to low pH. *Microbiology and Molecular Biology Reviews*, 67, 429-453.
- COTTER, P. D., HILL, C. & ROSS, R. P. 2005. Bacteriocins: developing innate immunity for food. *Nature Reviews Microbiology*, 3, 777-88.
- COTTER, P. D., ROSS, R. P. & HILL, C. 2013. Bacteriocins - a viable alternative to antibiotics? *Nature Reviews Microbiology*, 11, 95-105.
- COX, C. L., DOROGHAZI, J. R. & MITCHELL, D. A. 2015. The genomic landscape of ribosomal peptides containing thiazole and oxazole heterocycles. *BMC genomics*, 16, 778.
- DABOUR, N., ZIHLER, A., KHEADR, E., LACROIX, C. & FLISS, I. 2009. In vivo study on the effectiveness of pediocin PA-1 and *Pediococcus acidilactici* UL5 at inhibiting *Listeria monocytogenes*. *International journal of food microbiology*, 133, 225-233.
- DAWID, S., ROCHE, A. M. & WEISER, J. N. 2007. The blp bacteriocins of *Streptococcus pneumoniae* mediate intraspecies competition both in vitro and in vivo. *Infection and immunity*, 75, 443-451.
- DE KWAADSTENIET, M., DOESCHATE, K. & DICKS, L. 2009. Nisin F in the treatment of respiratory tract infections caused by *Staphylococcus aureus*. *Letters in applied microbiology*, 48, 65-70.
- DE OLIVEIRA, E. F., COSSU, A., TIKEKAR, R. V. & NITIN, N. 2017. Enhanced Antimicrobial Activity Based on a Synergistic Combination of Sublethal Levels of Stresses Induced by UV-A Light and Organic Acids. *Applied and Environmental Microbiology*, 83, e00383-17.
- DE WEIRD, R., CRABBE, A., ROOS, S., VOLLENWEIDER, S., LACROIX, C., VAN PIJCKEREN, J. P., BRITTON, R. A., SARKER, S., VAN DE WIELE, T. & NICKERSON, C. A. 2012. Glycerol supplementation enhances *L. reuteri*'s protective effect against *S. Typhimurium* colonization in a 3-D model of colonic epithelium. *PLoS One*, 7, e37116.
- DESHMUKH, P. & THORAT, P. 2013. Bacteriocins: A new trend in antimicrobial food packaging. *Int J Adv Res Eng App Sci*, 1, 1-12.
- DI MASCO, P., WEFERS, H., DO-THI, H.-P., LAFLEUR, M. V. M. & SIES, H. 1989. Singlet molecular oxygen causes loss of biological activity in plasmid and bacteriophage DNA and induces single-strand breaks. *Biochimica et Biophysica Acta (BBA)-Gene Structure and Expression*, 1007, 151-157.
- DIAZ-RUIZ, G., OMAR, N. B., ABRIQUEL, H., CANTILDE, M. M. & GALVEZ, A. 2012. Inhibition of *Listeria monocytogenes* and *Escherichia coli* by bacteriocin-producing *Lactobacillus plantarum* EC52 in a meat sausage model system. *African Journal of Microbiology Research*, 6, 1103-1108.
- DIBNER, J. & BUTTIN, P. 2002. Use of organic acids as a model to study the impact of gut microflora on nutrition and metabolism. *Journal of Applied Poultry Research*, 11, 453-463.
- DICKS, L., HEUNIS, T., VAN STADEN, D., BRAND, A., NOLL, K. S. & CHIKINDAS, M. 2011. Medical and personal care applications of bacteriocins produced by lactic acid bacteria. *Prokaryotic Antimicrobial Peptides*. Springer.
- DOBSON, A., COTTER, P. D., ROSS, R. P. & HILL, C. 2012. Bacteriocin production: a probiotic trait? *Applied and Environmental Microbiology*, 78, 1-6.
- DONIA, M. S., CIMERMANCIC, P., SCHULZE, C. J., BROWN, L. C. W., MARTIN, J., MITREVA, M., CLARDY, J., LININGTON, R. G. & FISCHBACH, M. A. 2014. A systematic analysis of biosynthetic gene clusters in the human microbiome reveals a common family of antibiotics. *Cell*, 158, 1402-1414.

- DRAPER, L. A., DEEGAN, L. H., HILL, C., COTTER, P. D. & ROSS, R. P. 2012. Insights into lantibiotic immunity provided by bioengineering of LtnI. *Antimicrobial agents and chemotherapy*, 56, 5122-5133.
- ELSHAGHABEE, F. M., BOCKELMANN, W., MESKE, D., DE VRESE, M., WALTE, H.-G., SCHREZENMEIR, J. & HELLER, K. J. 2016. Ethanol production by selected intestinal microorganisms and lactic acid bacteria growing under different nutritional conditions. *Frontiers in microbiology*, 7.
- ENGEVIK, M. & VERSALOVIC, J. 2017. Biochemical Features of Beneficial Microbes: Foundations for Therapeutic Microbiology. *Microbiology spectrum*, 5.
- EZEJI, C. & OJIMELUKWE, P. 1993. Effect of fermentation on the nutritional quality and functional properties of infant food formulations prepared from bambarra-groundnut, fluted-pumpkin and millet seeds. *Plant foods for human nutrition*, 44, 267-276.
- FERNÁNDEZ-CRUZ, M. L., MARTÍN-CABREJAS, I., PÉREZ-DEL PALACIO, J., GAYA, P., DÍAZ-NAVARRO, C., NAVAS, J. M., MEDINA, M. & ARQUÉS, J. L. 2016. In vitro toxicity of reuterin, a potential food biopreservative. *Food and Chemical Toxicology*, 96, 155-159.
- FERREIRA, M. & LUND, B. 1996. The effect of nisin on *Listeria monocytogenes* in culture medium and long-life cottage cheese. *Letters in applied microbiology*, 22, 433-438.
- FIELD, D., COTTER, P. D., ROSS, R. P. & HILL, C. 2015. Bioengineering of the model lantibiotic nisin. *Bioengineered*, 6, 187-192.
- FIMLAND, N., ROGNE, P., FIMLAND, G., NISSEN-MEYER, J. & KRISTIANSEN, P. E. 2008. Three-dimensional structure of the two peptides that constitute the two-peptide bacteriocin plantaricin EF. *Biochimica et Biophysica Acta (BBA)-Proteins and Proteomics*, 1784, 1711-1719.
- FINNEGAN, M., LINLEY, E., DENYER, S. P., MCDONNELL, G., SIMONS, C. & MAILLARD, J.-Y. 2010. Mode of action of hydrogen peroxide and other oxidizing agents: differences between liquid and gas forms. *Journal of Antimicrobial Chemotherapy*, 65, 2108-2115.
- FLYNN, S., VAN SINDEREN, D., THORNTON, G. M., HOLO, H., NES, I. F. & COLLINS, J. K. 2002. Characterization of the genetic locus responsible for the production of ABP-118, a novel bacteriocin produced by the probiotic bacterium *Lactobacillus salivarius* subsp. *salivarius* UCC118. *Microbiology*, 148, 973-84.
- FOLIGNE, B., NUTTEN, S., GRANGETTE, C., DENNIN, V., GOUDERCOURT, D., POIRET, S., DEWULF, J., BRASSART, D., MERCENIER, A. & POT, B. 2007. Correlation between in vitro and in vivo immunomodulatory properties of lactic acid bacteria. *World journal of gastroenterology: WJG*, 13, 236.
- GÁLVEZ, A., MAQUEDA, M., MARTÍNEZ-BUENO, M. & VALDIVIA, E. 1991. Permeation of bacterial cells, permeation of cytoplasmic and artificial membrane vesicles, and channel formation on lipid bilayers by peptide antibiotic AS-48. *Journal of bacteriology*, 173, 886-892.
- GÄNZLE, M. 2004. Reutericyclin: biological activity, mode of action, and potential applications. *Applied microbiology and biotechnology*, 64, 326-332.
- GÄNZLE, M. G. 2015. Lactic metabolism revisited: metabolism of lactic acid bacteria in food fermentations and food spoilage. *Current Opinion in Food Science*, 2, 106-117.
- GÄNZLE, M. G. & VOGEL, R. F. 2003. Contribution of reutericyclin production to the stable persistence of *Lactobacillus reuteri* in an industrial sourdough fermentation. *International journal of food microbiology*, 80, 31-45.
- GAO, Y., VAN BELKUM, M. J. & STILES, M. E. 1999. The outer membrane of Gram-negative bacteria inhibits antibacterial activity of brochocin-C. *Applied and Environmental Microbiology*, 65, 4329-4333.
- GOLDSTEIN, B. P., WEI, J., GREENBERG, K. & NOVICK, R. 1998. Activity of nisin against *Streptococcus pneumoniae*, in vitro, and in a mouse infection model. *The Journal of antimicrobial chemotherapy*, 42, 277-278.
- GÓMEZ-SALA, B., HERRANZ, C., DÍAZ-FREITAS, B., HERNÁNDEZ, P. E., SALA, A. & CINTAS, L. M. 2016. Strategies to increase the hygienic and economic value of fresh fish:

- Biopreservation using lactic acid bacteria of marine origin. *International journal of food microbiology*, 223, 41-49.
- GONG, Z., LUNA, Y., YU, P. & FAN, H. 2014. Lactobacilli inactivate *Chlamydia trachomatis* through lactic acid but not H₂O₂. *PLoS One*, 9, e107758.
- GOUGH, R., GÓMEZ-SALA, B., O'CONNOR, P. M., REA, M. C., MIAO, S., HILL, C. & BRODKORB, A. 2017. A Simple Method for the Purification of Nisin. *Probiotics and antimicrobial proteins*, 9, 363-369.
- GRILLI, E., MESSINA, M., CATELLI, E., MORLACCHINI, M. & PIVA, A. 2009. Pediocin A improves growth performance of broilers challenged with *Clostridium perfringens*. *Poultry science*, 88, 2152-2158.
- HARBER, P., SAECHAO, K. & BOOMUS, C. 2006. Diacetyl-induced lung disease. *Toxicological reviews*, 25, 261-272.
- HAVARSTEIN, L. S., DIEP, D. B. & NES, I. F. 1995. A family of bacteriocin ABC transporters carry out proteolytic processing of their substrates concomitant with export. *Mol Microbiol*, 16, 229-40.
- HAWES, S. E., HILLIER, S. L., BENEDETTI, J., STEVENS, C. E., KOUTSKY, L. A., WØLNER-HANSEN, P. & HOLMES, K. K. 1996. Hydrogen peroxide—producing lactobacilli and acquisition of vaginal infections. *Journal of Infectious Diseases*, 174, 1058-1063.
- HEALY, B., FIELD, D., O'CONNOR, P. M., HILL, C., COTTER, P. D. & ROSS, R. P. 2013. Intensive mutagenesis of the nisin hinge leads to the rational design of enhanced derivatives. *PloS one*, 8, e79563.
- HEATH, L. S., HEATH, H. E., LEBLANC, P. A., SMITHBERG, S. R., DUFOUR, M., SIMMONDS, R. S. & SLOAN, G. L. 2004. The streptococcal enzyme zoocin A is a penicillin-binding protein. *FEMS microbiology letters*, 236, 205-211.
- HELANDER, I. M., VON WRIGHT, A. & MATTILA-SANDHOLM, T. 1997. Potential of lactic acid bacteria and novel antimicrobials against Gram-negative bacteria. *Trends in Food Science & Technology*, 8, 146-150.
- HEMU, X., QIU, Y., NGUYEN, G. K. & TAM, J. P. 2016. Total synthesis of circular bacteriocins by butelase 1. *J. Am. Chem. Soc*, 138, 6968-6971.
- HENDERSON, J. T., CHOPKO, A. L. & VAN WASSENAAR, P. D. 1992. Purification and primary structure of pediocin PA-1 produced by *Pediococcus acidilactici* PAC-1.0. *Archives of biochemistry and biophysics*, 295, 5-12.
- HERRANZ, C. & DRIESSEN, A. J. 2005. Sec-mediated secretion of bacteriocin enterocin P by *Lactococcus lactis*. *Applied and environmental microbiology*, 71, 1959-1963.
- HERTZBERGER, R., ARENTS, J., DEKKER, H. L., PRIDMORE, R. D., GYSLER, C., KLEEREBEZEM, M. & DE MATTOS, M. J. T. 2014. H₂O₂ production in species of the *Lactobacillus acidophilus* group: a central role for a novel NADH-dependent flavin reductase. *Applied and environmental microbiology*, 80, 2229-2239.
- HEUNIS, T. D., SMITH, C. & DICKS, L. M. 2013. Evaluation of a nisin-eluting nanofiber scaffold to treat *Staphylococcus aureus*-induced skin infections in mice. *Antimicrobial agents and chemotherapy*, 57, 3928-3935.
- HIRSHFIELD, I. N., TERZULLI, S. & O'BYRNE, C. 2003. Weak organic acids: a panoply of effects on bacteria. *Sci Prog*, 86, 245-69.
- HOOVEN, H. W., DOELAND, C., KAMP, M., KONINGS, R. N., HILBERS, C. W. & VEN, F. J. 1996. Three-Dimensional Structure of the Lantibiotic Nisin in the Presence of Membrane-Mimetic Micelles of Dodecylphosphocholine and of Sodium Dodecylsulphate. *The FEBS Journal*, 235, 382-393.
- HOWELL, T., FIORELLINI, J., BLACKBURN, P., PROJAN, S., HARPE, J. & WILLIAMS, R. 1993. The effect of a mouthrinse based on nisin, a bacteriocin, on developing plaque and gingivitis in beagle dogs. *Journal of Clinical Periodontology*, 20, 335-339.
- HSIAO, H. L., LIN, S. B., CHEN, L. C. & CHEN, H. H. 2016. Hurdle effect of antimicrobial activity achieved by time differential releasing of nisin and chitosan hydrolysates from bacterial cellulose. *Journal of food science*, 81.

- HÜTT, P., LAPP, E., ŠTŠEPETOVA, J., SMIDT, I., TAELEMA, H., BOROVKOVA, N., OOPKAUP, H., AHELIK, A., RÖÖP, T. & HOIDMETS, D. 2016. Characterisation of probiotic properties in human vaginal lactobacilli strains. *Microbial ecology in health and disease*, 27, 30484.
- IMLAY, J. A., CHIN, S. M. & LINN, S. 1988. Toxic DNA damage by hydrogen peroxide through the Fenton reaction in vivo and in vitro. *Science*, 240, 640-642.
- IRKIN, R. & ESMER, O. K. 2015. Novel food packaging systems with natural antimicrobial agents. *Journal of food science and technology*, 52, 6095-6111.
- JIMENEZ-DIAZ, R., RIOS-SANCHEZ, R. M., DESMAZEAUD, M., RUIZ-BARBA, J. L. & PIARD, J. C. 1993. Plantaricins S and T, Two New Bacteriocins Produced by *Lactobacillus plantarum* LPCO10 Isolated from a Green Olive Fermentation. *Applied and Environmental Microbiology*, 59, 1416-24.
- JOERGER, M. C. & KLAENHAMMER, T. R. 1990. Cloning, expression, and nucleotide sequence of the *Lactobacillus helveticus* 481 gene encoding the bacteriocin helveticin J. *J Bacteriol*, 172, 6339-47.
- JÓZEFIAK, D., KIEROŃCZYK, B., JUŚKIEWICZ, J., ZDUŃCZYK, Z., RAWSKI, M., DŁUGOSZ, J., SIP, A. & HØJBERG, O. 2013. Dietary nisin modulates the gastrointestinal microbial ecology and enhances growth performance of the broiler chickens. *PloS one*, 8, e85347.
- JUNEJA, V. & THIPPAREDDI, H. 2004. Inhibitory effects of organic acid salts on growth of *Clostridium perfringens* from spore inocula during chilling of marinated ground turkey breast. *International journal of food microbiology*, 93, 155-163.
- KANG, B. S., SEO, J.-G., LEE, G.-S., KIM, J.-H., KIM, S. Y., HAN, Y. W., KANG, H., KIM, H. O., RHEE, J. H. & CHUNG, M.-J. 2009. Antimicrobial activity of enterocins from *Enterococcus faecalis* SL-5 against *Propionibacterium acnes*, the causative agent in *acne vulgaris*, and its therapeutic effect. *The Journal of Microbiology*, 47, 101-109.
- KANG, D.-H. & FUNG, D. Y. 1999. Effect of diacetyl on controlling *Escherichia coli* O157: H7 and *Salmonella* Typhimurium in the presence of starter culture in a laboratory medium and during meat fermentation. *Journal of food protection*, 62, 975-979.
- KATO, T., MAEDA, K., KASUYA, H. & MATSUDA, T. 1999. Complete growth inhibition of *Bacillus subtilis* by nisin-producing lactococci in fermented soybeans. *Bioscience, biotechnology, and biochemistry*, 63, 642-647.
- KELLY, W., ASMUNDSON, R. & HUANG, C. 1996. Characterization of plantaricin KW30, a bacteriocin produced by *Lactobacillus plantarum*. *Journal of Applied Microbiology*, 81, 657-662.
- KIRKPATRICK, C., MAURER, L. M., OYELAKIN, N. E., YONCHEVA, Y. N., MAURER, R. & SLONCZEWSKI, J. L. 2001. Acetate and formate stress: opposite responses in the proteome of *Escherichia coli*. *J Bacteriol*, 183, 6466-77.
- KJOS, M., SALEHIAN, Z., NES, I. F. & DIEP, D. B. 2010. An extracellular loop of the mannose phosphotransferase system component IIC is responsible for specific targeting by class IIa bacteriocins. *J Bacteriol*, 192, 5906-13.
- KLOSTERMANN, K., CRISPIE, F., FLYNN, J., MEANEY, W. J., ROSS, R. P. & HILL, C. 2010. Efficacy of a teat dip containing the bacteriocin lactacin 3147 to eliminate Gram-positive pathogens associated with bovine mastitis. *Journal of dairy research*, 77, 231-238.
- KNIPE, C. L. & RUST, R. E. 2009. *Thermal processing of ready-to-eat meat products*, John Wiley & Sons.
- KOMMINENI, S., BRETL, D. J., LAM, V., CHAKRABORTY, R., HAYWARD, M., SIMPSON, P., CAO, Y., BOUSOUNIS, P., KRISTICH, C. J. & SALZMAN, N. H. 2015. Bacteriocin production augments niche competition by enterococci in the mammalian gastrointestinal tract. *Nature*.
- LANCIOTTI, R., PATRIGNANI, F., BAGNOLINI, F., GUERZONI, M. & GARDINI, F. 2003. Evaluation of diacetyl antimicrobial activity against *Escherichia coli*, *Listeria monocytogenes* and *Staphylococcus aureus*. *Food Microbiology*, 20, 537-543.
- LANGER, R. & FOLKMAN, J. 1976. Polymers for the sustained release of proteins and other macromolecules. *Nature*, 263, 797.

- LARIDI, R., KHEADR, E., BENECH, R.-O., VUILLEMARD, J., LACROIX, C. & FLISS, I. 2003. Liposome encapsulated nisin Z: optimization, stability and release during milk fermentation. *International dairy journal*, 13, 325-336.
- LEE, S. W., MITCHELL, D. A., MARKLEY, A. L., HENSLER, M. E., GONZALEZ, D., WOHLRAB, A., DORRESTEIN, P. C., NIZET, V. & DIXON, J. E. 2008. Discovery of a widely distributed toxin biosynthetic gene cluster. *Proceedings of the National Academy of Sciences U S A*, 105, 5879-84.
- LEE, Y.-L., CESARIO, T., OWENS, J., SHANBROM, E. & THRUPP, L. D. 2002. Antibacterial activity of citrate and acetate. *Nutrition*, 18, 665-666.
- LEER, R. J., VAN DER VOSSSEN, J. M., VAN GIEZEN, M., VAN NOORT JOHANNES, M. & POUWELS, P. H. 1995. Genetic analysis of acidocin B, a novel bacteriocin produced by *Lactobacillus acidophilus*. *Microbiology*, 141, 1629-1635.
- LEROY, F. & DE VUYST, L. 2004. Lactic acid bacteria as functional starter cultures for the food fermentation industry. *Trends in Food Science & Technology*, 15, 67-78.
- LESERMAN, L. D., BARBET, J., KOURILSKY, F. & WEINSTEIN, J. N. 1980. Targeting to cells of fluorescent liposomes covalently coupled with monoclonal antibody or protein A. *Nature*, 288, 602.
- LETZEL, A.-C., PIDOT, S. J. & HERTWECK, C. 2014. Genome mining for ribosomally synthesized and post-translationally modified peptides (RiPPs) in anaerobic bacteria. *BMC Genomics*, 15, 1.
- LIN, X. B., LOHANS, C. T., DUAR, R., ZHENG, J., VEDERAS, J. C., WALTER, J. & GÄNZLE, M. 2015. Genetic determinants of reutericyclin biosynthesis in *Lactobacillus reuteri*. *Applied and environmental microbiology*, 81, 2032-2041.
- LINDGREN, S. E. & DOBROGOSZ, W. J. 1990. Antagonistic activities of lactic acid bacteria in food and feed fermentations. *FEMS Microbiology Letters*, 87, 149-163.
- LINLEY, E., DENYER, S. P., MCDONNELL, G., SIMONS, C. & MAILLARD, J.-Y. 2012. Use of hydrogen peroxide as a biocide: new consideration of its mechanisms of biocidal action. *Journal of antimicrobial chemotherapy*, 67, 1589-1596.
- LIU, F. & YU, B. 2015. Efficient production of reuterin from glycerol by magnetically immobilized *Lactobacillus reuteri*. *Applied microbiology and biotechnology*, 99, 4659-4666.
- LIU, X., BASU, U., MILLER, P. & MCMULLEN, L. M. 2014. Stress response and adaptation of *Listeria monocytogenes* 08-5923 exposed to a sublethal dose of carnocyclin A. *Applied and environmental microbiology*, 80, 3835-3841.
- LÓPEZ-CUELLAR, M. D. R., RODRÍGUEZ-HERNÁNDEZ, A.-I. & CHAVARRÍA-HERNÁNDEZ, N. 2016. LAB bacteriocin applications in the last decade. *Biotechnology & Biotechnological Equipment*, 30, 1039-1050.
- LORETZ, M., STEPHAN, R. & ZWEIFEL, C. 2011. Antibacterial activity of decontamination treatments for cattle hides and beef carcasses. *Food Control*, 22, 347-359.
- LOURENÇO, A., KAMNETZ, M. B., GADOTTI, C. & DIEZ-GONZALEZ, F. 2017. Antimicrobial treatments to control *Listeria monocytogenes* in queso fresco. *Food microbiology*, 64, 47-55.
- MACA, J., MILLER, R. & ACUFF, G. 1997. Microbiological, Sensory and Chemical Characteristics of Vacuum-Packaged Ground Beef Patties Treated with Salts of Organic Acids. *Journal of Food Science*, 62, 591-596.
- MAKHAL, S., KANAWJIA, S. & GIRI, A. 2015. Effect of microGARD on keeping quality of direct acidified Cottage cheese. *Journal of food science and technology*, 52, 936-943.
- MARSH, A. J., O'SULLIVAN, O., ROSS, R. P., COTTER, P. D. & HILL, C. 2010. In silico analysis highlights the frequency and diversity of type 1 lantibiotic gene clusters in genome sequenced bacteria. *BMC Genomics*, 11, 679.
- MARTIN-VISSCHER, L. A., VAN BELKUM, M. J., GARNEAU-TSODIKOVA, S., WHITTAL, R. M., ZHENG, J., MCMULLEN, L. M. & VEDERAS, J. C. 2008. Isolation and characterization of carnocyclin a, a novel circular bacteriocin produced by *Carnobacterium maltaromaticum* UAL307. *Appl Environ Microbiol*, 74, 4756-63.

- MARTIN JR, H. L., RICHARDSON, B. A., NYANGE, P. M., LAVREYS, L., HILLIER, S. L., CHOCHAN, B., MANDALIYA, K., NDINYA-ACHOLA, J. O., BWAYO, J. & KREISS, J. 1999. Vaginal lactobacilli, microbial flora, and risk of human immunodeficiency virus type 1 and sexually transmitted disease acquisition. *Journal of Infectious Diseases*, 180, 1863-1868.
- MARTIN, R., OLIVARES, M., MARIN, M., XAUS, J., FERNÁNDEZ, L. & RODRIGUEZ, J. 2005. Characterization of a reuterin-producing *Lactobacillus coryniformis* strain isolated from a goat's milk cheese. *International journal of food microbiology*, 104, 267-277.
- MARTINEZ, B., SUAREZ, J. E. & RODRIGUEZ, A. 1996. Lactococcin 972 : a homodimeric lactococcal bacteriocin whose primary target is not the plasma membrane. *Microbiology*, 142 (Pt 9), 2393-8.
- MCDONNELL, G. & RUSSELL, A. D. 1999. Antiseptics and disinfectants: activity, action, and resistance. *Clinical microbiology reviews*, 12, 147-179.
- MCWILLIAM LEITCH, E. & STEWART, C. 2002. Susceptibility of *Escherichia coli* O157 and non-O157 isolates to lactate. *Letters in Applied Microbiology*, 35, 176-180.
- MILLETTE, M., CORNUT, G., DUPONT, C., SHARECK, F., ARCHAMBAULT, D. & LACROIX, M. 2008. Capacity of human nisin- and pediocin-producing lactic Acid bacteria to reduce intestinal colonization by vancomycin-resistant enterococci. *Appl Environ Microbiol*, 74, 1997-2003.
- MILLS, S., GRIFFIN, C., O'CONNOR, P., SERRANO, L., MEIJER, W. C., HILL, C. & ROSS, R. P. 2017. A multibacteriocin cheese starter system, comprising nisin and lactacin 3147 in *Lactococcus lactis*, in combination with plantaricin from *Lactobacillus plantarum*. *Applied and environmental microbiology*, 83, e00799-17.
- MILLS, S., STANTON, C., HILL, C. & ROSS, R. 2011. New developments and applications of bacteriocins and peptides in foods. *Annual review of food science and technology*, 2, 299-329.
- MITCHELL, C., FREDRICKS, D., AGNEW, K. & HITTI, J. 2015. Hydrogen-peroxide producing lactobacilli are associated with lower levels of vaginal IL1 β , independent of bacterial vaginosis. *Sexually transmitted diseases*, 42, 358.
- MOLS, M. & ABEE, T. 2011. *Bacillus cereus* responses to acid stress. *Environmental microbiology*, 13, 2835-2843.
- MOLS, M., VAN KRANENBURG, R., TEMPELAARS, M. H., VAN SCHAIK, W., MOEZELAAR, R. & ABEE, T. 2010. Comparative analysis of transcriptional and physiological responses of *Bacillus cereus* to organic and inorganic acid shocks. *International journal of food microbiology*, 137, 13-21.
- MORITA, H., TOH, H., FUKUDA, S., HORIKAWA, H., OSHIMA, K., SUZUKI, T., MURAKAMI, M., HISAMATSU, S., KATO, Y. & TAKIZAWA, T. 2008. Comparative genome analysis of *Lactobacillus reuteri* and *Lactobacillus fermentum* reveal a genomic island for reuterin and cobalamin production. *DNA research*, 15, 151-161.
- MOTA-MEIRA, M., LACROIX, C., LAPOINTE, G. & LAVOIE, M. C. 1997. Purification and structure of mutacin B-Ny266: a new lantibiotic produced by *Streptococcus mutans*. *FEBS letters*, 410, 275-279.
- NILSEN, T., NES, I. F. & HOLO, H. 2003. Enterolysin A, a cell wall-degrading bacteriocin from *Enterococcus faecalis* LMG 2333. *Appl Environ Microbiol*, 69, 2975-84.
- NISSEN-MEYER, J., OPPEGARD, C., ROGNE, P., HAUGEN, H. S. & KRISTIANSEN, P. E. 2010. Structure and Mode-of-Action of the Two-Peptide (Class-IIb) Bacteriocins. *Probiotics and Antimicrobial Proteins*, 2, 52-60.
- NISSEN-MEYER, J., OPPEGÅRD, C., ROGNE, P., HAUGEN, H. S. & KRISTIANSEN, P. E. 2011. The two-peptide (Class-IIb) bacteriocins: genetics, biosynthesis, structure, and mode of action. *Prokaryotic Antimicrobial Peptides*. Springer.
- NORRIS, G. E. & PATCHETT, M. L. 2016. The glycocins: in a class of their own. *Current opinion in structural biology*, 40, 112-119.
- O'HANLON, D. E., LANIER, B. R., MOENCH, T. R. & CONE, R. A. 2010. Cervicovaginal fluid and semen block the microbicidal activity of hydrogen peroxide produced by vaginal lactobacilli. *BMC infectious diseases*, 10, 120.

- O'HANLON, D. E., MOENCH, T. R. & CONE, R. A. 2011. In vaginal fluid, bacteria associated with bacterial vaginosis can be suppressed with lactic acid but not hydrogen peroxide. *BMC infectious diseases*, 11, 200.
- O'SHEA, E. F., O'CONNOR, P. M., O'SULLIVAN, O., COTTER, P. D., ROSS, R. P. & HILL, C. 2013. Bactofencin A, a new type of cationic bacteriocin with unusual immunity. *MBio*, 4, e00498-13.
- O'SULLIVAN, L., MORGAN, S., ROSS, R. & HILL, C. 2002. Elevated enzyme release from lactococcal starter cultures on exposure to the lantibiotic lacticin 481, produced by *Lactococcus lactis* DPC5552. *Journal of dairy science*, 85, 2130-2140.
- O'NEILL, J. 2014. Antimicrobial resistance: tackling a crisis for the health and wealth of nations. *The Review on Antimicrobial Resistance*, 20.
- O'SULLIVAN, L., ROSS, R. P. & HILL, C. 2002. Potential of bacteriocin-producing lactic acid bacteria for improvements in food safety and quality. *Biochimie*, 84, 593-604.
- OH, D.-H. & MARSHALL, D. L. 1993. Antimicrobial activity of ethanol, glycerol monolaurate or lactic acid against *Listeria monocytogenes*. *International journal of food microbiology*, 20, 239-246.
- OKUDA, K.-I., ZENDO, T., SUGIMOTO, S., IWASE, T., TAJIMA, A., YAMADA, S., SONOMOTO, K. & MIZUNOE, Y. 2013. Effects of bacteriocins on methicillin-resistant *Staphylococcus aureus* biofilm. *Antimicrobial agents and chemotherapy*, 57, 5572-5579.
- OLASUPO, N., FITZGERALD, D., GASSON, M. & NARBAD, A. 2003. Activity of natural antimicrobial compounds against *Escherichia coli* and *Salmonella enterica* serovar Typhimurium. *Letters in Applied Microbiology*, 37, 448-451.
- OMAN, T. J. & VAN DER DONK, W. A. 2010. Follow the leader: the use of leader peptides to guide natural product biosynthesis. *Nat Chem Biol*, 6, 9-18.
- OPPEGARD, C., FIMLAND, G., ANONSEN, J. H. & NISSEN-MEYER, J. 2015. The Pediocin PA-1 Accessory Protein Ensures Correct Disulfide Bond Formation in the Antimicrobial Peptide Pediocin PA-1. *Biochemistry*, 54, 2967-74.
- ORGANIZATION, W. H. 2015. WHO estimates of the global burden of foodborne diseases: foodborne disease burden epidemiology reference group 2007-2015.
- ORGANIZATION, W. H. 2017. Antibacterial agents in clinical development: an analysis of the antibacterial clinical development pipeline, including tuberculosis.
- OSHIMA, S., REA, M. C., LOTHE, S., MORGAN, S., BEGLEY, M., O'CONNOR, P. M., FITZSIMMONS, A., KAMIKADO, H., WALTON, R. & ROSS, R. P. 2012. Efficacy of organic acids, bacteriocins, and the lactoperoxidase system in inhibiting the growth of *Cronobacter* spp. in rehydrated infant formula. *Journal of food protection*, 75, 1734-1742.
- PAPAGIANNI, M. & ANASTASIADOU, S. 2009. Pediocins: The bacteriocins of *Pediococci*. Sources, production, properties and applications. *Microbial Cell Factories*, 8, 3-3.
- PERÉZ-DÍAZ, I., BREIDT, F., BUESCHER, R., ARROYO-LÓPEZ, F., JIMÉNEZ-DÍAZ, R., GARRIDO-FERNÁNDEZ, A., BAUTISTA-GALLEGO, J., YOON, S. & JOHANNINGSMEIRE, S. 2013. Fermented and acidified vegetables. *Compendium of methods for the microbiological examination of foods*, 4th edn. American Public Health Association, Washington, DC, 521-532.
- PINEIRO, M. & STANTON, C. 2007. Probiotic bacteria: legislative framework—requirements to evidence basis. *The Journal of nutrition*, 137, 850S-853S.
- QUITMANN, H., FAN, R. & CZERMAK, P. 2013. Acidic organic compounds in beverage, food, and feed production. *Biotechnology of Food and Feed Additives*. Springer.
- REA, M. C., SIT, C. S., CLAYTON, E., O'CONNOR, P. M., WHITTAL, R. M., ZHENG, J., VEDERAS, J. C., ROSS, R. P. & HILL, C. 2010. Thuricin CD, a posttranslationally modified bacteriocin with a narrow spectrum of activity against *Clostridium difficile*. *Proceedings of the National Academy of Sciences USA*. United States.
- RINK, R., ARKEMA-METER, A., BAUDOIN, I., POST, E., KUIPERS, A., NELEMANS, S., AKANBI, M. H. J. & MOLL, G. 2010. To protect peptide pharmaceuticals against peptidases. *Journal of pharmacological and toxicological methods*, 61, 210-218.

- ROE, A. J., O'BYRNE, C., MCLAGGAN, D. & BOOTH, I. R. 2002. Inhibition of *Escherichia coli* growth by acetic acid: a problem with methionine biosynthesis and homocysteine toxicity. *Microbiology*, 148, 2215-22.
- ROGERS, L. & WHITTIER, E. 1928. Limiting factors in the lactic fermentation. *Journal of Bacteriology*, 16, 211.
- ROHDE, B. H. & QUADRI, L. E. 2006. Functional characterization of a three-component regulatory system involved in quorum sensing-based regulation of peptide antibiotic production in *Carnobacterium maltaromaticum*. *BMC microbiology*, 6, 93.
- ROSS, R. P., MORGAN, S. & HILL, C. 2002. Preservation and fermentation: past, present and future. *International journal of food microbiology*, 79, 3-16.
- RYAN, M. P., REA, M. C., HILL, C. & ROSS, R. P. 1996. An application in cheddar cheese manufacture for a strain of *Lactococcus lactis* producing a novel broad-spectrum bacteriocin, lacticin 3147. *Applied and Environmental Microbiology*, 62, 612-619.
- SALIH, M., SANDINE, W. & AYRES, J. 1990. Inhibitory Effects of Microgard™ on Yogurt and Cottage Cheese Spoilage Organisms1. *Journal of dairy science*, 73, 887-893.
- SALLAM, K. I. 2007. Antimicrobial and antioxidant effects of sodium acetate, sodium lactate, and sodium citrate in refrigerated sliced salmon. *Food control*, 18, 566-575.
- SALMOND, C. V., KROLL, R. G. & BOOTH, I. R. 1984. The effect of food preservatives on pH homeostasis in *Escherichia coli*. *Microbiology*, 130, 2845-2850.
- SAUVAGEOT, N., GOUFFI, K., LAPLACE, J.-M. & AUFRAY, Y. 2000. Glycerol metabolism in *Lactobacillus collinoides*: production of 3-hydroxypropionaldehyde, a precursor of acrolein. *International journal of food microbiology*, 55, 167-170.
- SCANNELL, A. G., HILL, C., ROSS, R., MARX, S., HARTMEIER, W. & ARENDT, E. K. 2000. Development of bioactive food packaging materials using immobilised bacteriocins Lacticin 3147 and Nisaplin®. *International journal of food microbiology*, 60, 241-249.
- SCHAEFER, L., AUCHTUNG, T. A., HERMANS, K. E., WHITEHEAD, D., BORHAN, B. & BRITTON, R. A. 2010. The antimicrobial compound reuterin (3-hydroxypropionaldehyde) induces oxidative stress via interaction with thiol groups. *Microbiology*, 156, 1589-1599.
- SCELLENBERG, J. J., DUMONCEAUX, T. J., HILL, J. E., KIMANI, J., JAOKO, W., WACHIHI, C., MUNGAI, J. N., LANE, M., FOWKE, K. R. & BALL, T. B. 2012. Selection, phenotyping and identification of acid and hydrogen peroxide producing bacteria from vaginal samples of Canadian and East African women. *PloS one*, 7, e41217.
- SCHÜTZ, H. & RADLER, F. 1984. Anaerobic reduction of glycerol to propanediol-1.3 by *Lactobacillus brevis* and *Lactobacillus buchneri*. *Systematic and Applied Microbiology*, 5, 169-178.
- SEARS, P., SMITH, B., STEWART, W., GONZALEZ, R., RUBINO, S., GUSIK, S., KULISEK, E., PROJAN, S. & BLACKBURN, P. 1992. Evaluation of a nisin-based germicidal formulation on teat skin of live cows. *Journal of dairy science*, 75, 3185-3190.
- SETTANNI, L. & CORSETTI, A. 2008. Application of bacteriocins in vegetable food biopreservation. *International journal of food microbiology*, 121, 123-138.
- SISSONS, C., WONG, L. & CUTRESS, T. 1996. Inhibition by ethanol of the growth of biofilm and dispersed microcosm dental plaques. *Archives of oral biology*, 41, 27-34.
- SLININGER, P. J., BOTHAST, R. J. & SMILEY, K. L. 1983. Production of 3-hydroxypropionaldehyde from glycerol. *Applied and environmental microbiology*, 46, 62-67.
- STERN, N., SVETOCH, E., ERUSLANOV, B., PERELYGIN, V., MITSEVICH, E., MITSEVICH, I., POKHILENKO, V., LEVCHUK, V., SVETOCH, O. & SEAL, B. 2006. Isolation of a *Lactobacillus salivarius* strain and purification of its bacteriocin, which is inhibitory to *Campylobacter jejuni* in the chicken gastrointestinal system. *Antimicrobial agents and chemotherapy*, 50, 3111-3116.
- TAMARIT, J., CABISCOL, E. & ROS, J. 1998. Identification of the major oxidatively damaged proteins in *Escherichia coli* cells exposed to oxidative stress. *Journal of Biological Chemistry*, 273, 3027-3032.
- TODD, E. 1938. The differentiation of two distinct serological varieties of streptolysin, streptolysin O and streptolysin S. *The Journal of Pathology*, 47, 423-445.

- UMU, Ö. C., RUDI, K. & DIEP, D. B. 2017. Modulation of the gut microbiota by prebiotic fibres and bacteriocins. *Microbial ecology in health and disease*, 28, 1348886.
- VALLOR, A. C., ANTONIO, M. A., HAWES, S. E. & HILLIER, S. L. 2001. Factors associated with acquisition of, or persistent colonization by, vaginal lactobacilli: role of hydrogen peroxide production. *The Journal of infectious diseases*, 184, 1431-1436.
- VAN DER PLOEG, J. R. 2005. Regulation of bacteriocin production in *Streptococcus mutans* by the quorum-sensing system required for development of genetic competence. *Journal of bacteriology*, 187, 3980-3989.
- VAN HEMERT, S., MEIJERINK, M., MOLENAAR, D., BRON, P. A., DE VOS, P., KLEEREBEZEM, M., WELLS, J. M. & MARCO, M. L. 2010. Identification of *Lactobacillus plantarum* genes modulating the cytokine response of human peripheral blood mononuclear cells. *BMC microbiology*, 10, 293.
- VENUGOPAL, H., EDWARDS, P. J., SCHWALBE, M., CLARIDGE, J. K., LIBICH, D. S., STEPPER, J., LOO, T., PATCHETT, M. L., NORRIS, G. E. & PASCAL, S. M. 2011. Structural, dynamic, and chemical characterization of a novel S-glycosylated bacteriocin. *Biochemistry*, 50, 2748-55.
- VOLLENWEIDER, S. & LACROIX, C. 2004. 3-Hydroxypropionaldehyde: applications and perspectives of biotechnological production. *Applied Microbiology and Biotechnology*, 64, 16-27.
- WANG, H., ZHANG, R., CHENG, J., LIU, H., ZHAI, L. & JIANG, S. 2015. Functional effectiveness and diffusion behavior of sodium lactate loaded chitosan/poly (L-lactic acid) film with antimicrobial activity. *RSC Advances*, 5, 98946-98954.
- WARNECKE, T. & GILL, R. T. 2005. Organic acid toxicity, tolerance, and production in *Escherichia coli* biorefining applications. *Microbial Cell Factories*, 4, 25.
- WILLEY, J. M. & VAN DER DONK, W. A. 2007. Lantibiotics: peptides of diverse structure and function. *Annu Rev Microbiol*, 61, 477-501.
- YANG, Y., ZHAO, X., LE, M. H., ZIJLSTRA, R. T. & GÄNZLE, M. G. 2015. Reutericyclin producing *Lactobacillus reuteri* modulates development of fecal microbiota in weanling pigs. *Frontiers in microbiology*, 6.
- YOUNES, M., AGGETT, P., AGUILAR, F., CREBELL, R., DUSEMUND, B., FILIPIČ, M., FRUTOS, M. J., GALTIER, P., GUNDERT-REMY, U. & KUHNLE, G. G. 2017. Safety of nisin (E 234) as a food additive in the light of new toxicological data and the proposed extension of use. *EFSA Journal*, 15.
- YOUNG, K. M. & FOEGEDING, P. M. 1993. Acetic, lactic and citric acids and pH inhibition of *Listeria monocytogenes* Scott A and the effect on intracellular pH. *J Appl Bacteriol*, 74, 515-20.
- YUNMBAM, M. K. & ROBERTS, J. F. 1993. In vivo evaluation of reuterin and its combinations with suramin, melarsoprol, DL- α -difluoromethylornithine and bleomycin in mice infected with *Trypanosoma brucei brucei*. *Comparative Biochemistry and Physiology Part C: Comparative Pharmacology*, 105, 521-524.
- ZACHAROF, M. & LOVITT, R. 2012. Bacteriocins produced by lactic acid bacteria a review article. *APCBEE Procedia*, 2, 50-56.
- ZHANG, Q. & LIU, W. 2013. Biosynthesis of thiopeptide antibiotics and their pathway engineering. *Natural product reports*, 30, 218-226.
- ZHITNITSKY, D., ROSE, J. & LEWINSON, O. 2017. The highly synergistic, broad spectrum, antibacterial activity of organic acids and transition metals. *Scientific Reports*, 7.

**Chapter 2: Formicin – A Novel Broad
Spectrum Two-Component Lantibiotic
Produced by *Bacillus paralicheniformis* APC
1576**

Mass spectrometry and peptide purification was carried out by Ms. Paula O'Connor, genome assembly was carried out by Dr. Orla O'Sullivan

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Abstract

Bacteriocins represent a rather underutilised class of antimicrobials, despite often displaying activity against many drug resistant pathogens. Lantibiotics are a post-translationally modified class of bacteriocins, characterised by the presence of lanthionine and methyllanthionine bridges. In this study, a novel two-component lantibiotic was isolated and characterised. Formicin was isolated from *Bacillus paralicheniformis* APC 1576, an antimicrobial producing strain originally isolated from the intestine of a mackerel. Genome sequencing allowed for the detection of the formicin operon, and from this the formicin structural genes were identified, along with those involved in lantibiotic modification, transport and immunity. The identified bacteriocin was subsequently purified from the bacterial supernatant. Despite the degree of conservation seen amongst the entire class of two-component lantibiotics, the formicin peptides are unique in many respects. The formicin α peptide is far less hydrophobic than any of the equivalent lantibiotics, and with a charge of plus two it is one of the most positively charged α peptides. The β peptide is unique in that it is the only such peptide with a negative charge due to the presence of an aspartic acid residue in the C-terminus, possibly indicating a slight variation to the mode of action of the bacteriocin. Formicin also displays a broad spectrum of inhibition against Gram positive strains, inhibiting many clinically relevant pathogens such as *Staphylococcus aureus*, *Clostridium difficile* and *Listeria monocytogenes*. The range of inhibition displayed against many important pathogens indicates a potential therapeutic use against such strains where antibiotic resistance is such a growing concern.

Introduction

With the increased prevalence of many drug resistant bacterial strains, the development of new antimicrobials is becoming a growing necessity. One such class of antimicrobials which appear to be underrepresented in clinical applications are bacteriocins (Cotter et al., 2013). Unlike traditional antibiotics, bacteriocins are gene encoded and ribosomally-synthesised peptides. This makes them suitable for genetic manipulation, with the potential for novel and specialised drug design (Gillor et al., 2005). The spectrum of inhibition of bacteriocins can range from broad to narrow spectrum, the latter of which may allow for highly targeted antibacterial therapies which may reduce the collateral damage associated with the use of broad spectrum antibiotics (Rea et al., 2011).

The lantibiotics (*lanthionine containing antibiotics*) comprise a well-studied class of bacteriocins, the most notable of which is nisin (Rogers, 1928) which is commonly used as a food preservative. Lantibiotics are classified based on the presence of lanthionine or methyllanthionine bridges. In these peptides, serine and threonine residues are post-translationally modified and dehydrated to form 2,3-didehydroalanine (Dha) and 2,3-didehydrobutyrine (Dhb) residues. The thiol group of a cysteine residue subsequently reacts with the Dha or Dhb residues resulting in the formation of lanthionine or methyllanthionine thioether cross-links (Xie and van der Donk, 2004).

The lantibiotic gene cluster encodes an array of genes required for the modification, regulation and transport of the bacteriocin. Lantibiotics are divided into classes depending on the mechanism by which they are synthesised. Class I lantibiotics encode the enzymes LanB and LanC within the bacteriocin operon, where LanB catalyses the dehydration of the serine and threonine residues, whilst LanC catalyses the cyclization of the lanthionine rings. In Class II lantibiotics, LanM alone catalyses both dehydration and cyclization of the lantibiotics (Willey and van der Donk, 2007). LanR and LanK play key roles in the regulation of lantibiotic production (Lee et al., 2011). Once the mature lantibiotic is produced, its cleavage and transport is carried out by LanP and LanT

respectively (Escano et al., 2015). In some cases, LanT can carry out both leader sequence cleavage and peptide secretion functions (Furgerson Ihnken et al., 2008). Immunity to lantibiotics can be afforded by immunity proteins such as the lipoprotein LanI which likely binds the secreted lantibiotic, and the ABC transporter LanFEG which transports bacteriocin peptides from the membrane to the extracellular medium. Here LanF binds and hydrolyses ATP which provides the energy required for the transport of the bacteriocin through the LanEG membrane complex (Stein et al., 2005, Takala et al., 2004, Alkhatib et al., 2012). For a review on this class of bacteriocins see (Willey and van der Donk, 2007).

Within the lantibiotic class of bacteriocins exists a small subgroup of two-component lantibiotics. Such bacteriocins are produced by an array of genera, including *Staphylococcus* and *Lactobacillus* (Navaratna et al., 1998, Holo et al., 2001). Interestingly, of the few two-component lantibiotics which have been described, two of these bacteriocins identified prior to this study are produced by *Bacillus* species. Bacilli species are known to produce a vast range of antimicrobials, whether antibiotics (e.g. gramicidin, bacitracin) or bacteriocins (e.g. thuricin CD, mersacidin) (Katz and Demain, 1977, Rea et al., 2010, Chatterjee et al., 1992). The currently identified two-component lantibiotics include lacticin 3147 (*Lactococcus lactis*) (Ryan et al., 1996), lichenicidin (*Bacillus licheniformis*) (Begley et al., 2009, Dischinger et al., 2009), haloduracin (*Bacillus halodurans*) (McClerren et al., 2006), enterocin W (*Enterococcus faecalis*) (Sawa et al., 2012), plantaricin W (*Lactobacillus plantarum*) (Holo et al., 2001), BHT (*Streptococcus rattus*) (Hyink et al., 2005), Smb (*Streptococcus mutans*) (Yonezawa and Kuramitsu, 2005) and staphylococcin C55 (*Staphylococcus aureus*) (Navaratna et al., 1998). In this subclass of bacteriocins, the two peptides produced tend to act synergistically and usually display negligible antimicrobial activity on their own.

The mode of action of lacticin 3147 identifies a likely model for the mode of action of similarly structured lantibiotics. The α peptide of lacticin 3147 (Ltn α) resembles the globular lantibiotic mersacidin, mirroring its activity by binding to lipid II which acts as an important docking molecule. Binding to lipid II results in a conformational change of Ltn α , which presents a site to

which the β peptide (Ltn β) can then bind. Ltn β resembles an elongated lantibiotic, which, once recruited by Ltn α , inserts itself into the target membrane, inducing pore formation, which results in cell death. Here the cooperative activity of both peptides is necessary for optimal antimicrobial activity as the stability of the total bacteriocin-lipid II complex is important for both pore formation and the inhibition of cell wall biosynthesis (Martin et al., 2004, Wiedemann et al., 2006).

In this study we extend the class of two-component lantibiotics by identifying a novel bacteriocin known as formicin which is produced by a marine isolate, *Bacillus paralicheniformis* APC 1576. Whilst this lantibiotic resembles the previously described two-component lantibiotics, it contains a number of features which differentiate it from the rest of the class.

Results

Isolation of *B. paralicheniformis* APC 1576

B. paralicheniformis APC 1576 was isolated from the intestinal microbiota of a freshly caught mackerel. In an initial screen for bacteriocin production the strain was found to inhibit *L. delbrueckii* subsp. *bulgaricus* LMG 6901 in an overlay assay (Fig. 1(a)). In addition, cell free supernatants (CFS) also inhibited *L. delbrueckii* subsp. *bulgaricus* LMG 6901 in a well diffusion assay indicating that the antimicrobial substance was secreted by the cells into the media (Fig. 1(b)). Colony MS was used to determine the molecular masses of the peptides produced by the cell, however, the detected peptide masses (Fig. 1(c)) failed to match any previously characterised bacteriocin, including lichenicidin, a bacteriocin produced by *B. licheniformis* (Begley et al., 2009). Moreover, more than one source of antimicrobial activity was found following purification of the antimicrobial peptides. MALDI-TOF MS identified a molecule with a mass of 1422.54 Da, which displayed activity against *L. delbrueckii* subsp. *bulgaricus* LMG 6901 once purified; this mass correlates closely with that of bacitracin which is encoded on the genome. The production of more than one antimicrobial from *Bacillus* species is not unexpected. Therefore, in order to identify all potential antimicrobials with activity against *L. delbrueckii* subsp. *bulgaricus* LMG 6901 the genome of *B. paralicheniformis* APC 1576 was sequenced.

Identification of a Novel Two-Component Lantibiotic Operon

Once the draft genome was obtained, the sequence was analysed with BAGEL3 and antiSMASH to identify the antimicrobials encoded. Gene clusters encoding the antibiotics bacitracin, surfactin and fengycin were found within the genome. The strain likely produces at least one of these antimicrobials, as antifungal activity was also observed against *Aspergillus niger* in overlay assays (data not shown).

A novel lantibiotic operon was also identified within the genome of the strain (Fig. 2). This operon spans approximately 17 kb and was located on a single contig of the draft bacterial genome.

Two putative lantibiotic-encoding structural genes were identified on this operon. ORF1 (*frcA1*) encodes a 66 amino acid peptide and ORF3 (*frcA2*) encodes a 71 amino acid peptide. Analysis of the prepropeptides (including the bacteriocin leader sequence) of these lantibiotics shows the formicin A1 prepropeptide displayed 47.8% amino acid identity to the unmodified haloduracin A1 equivalent and 35.9% identity to the lantibiotic mersacidin. As the putative bacteriocin appears to be a two-component bacteriocin, two lantibiotic modification enzymes should be present. The order of the genes in the operon would suggest that ORF2 (*frcM1*) is the modification enzyme associated with *frcA1*. Upon analysis, this ORF displayed 38.7% identity to the haloduracin HalM1 modification enzyme. The second lantibiotic gene, ORF3 (*frcA2*), appears to resemble the elongated β peptides of the other two-component lantibiotics which are involved in membrane insertion (Wiedemann et al., 2006). Upon analysis, formicin A2 revealed 42.4% identity with the unmodified lichenicidin LchA2 prepropeptide. ORF4 (*frcM2*) encodes the modification enzyme which follows this structural peptide, and displayed 33.6% identity to the lichenicidin LchM2 modification enzyme.

ORF5 located downstream of LchM2 is predicted to encode a lantibiotic transporter, displaying 52.5% identity to the haloduracin transporter, HalT. In addition to its function in bacteriocin transport, a sequence encoding a C39 peptidase domain (cd02425) can also be found within the gene, this is likely involved in the cleavage of the leader sequence from the prebacteriocin. BLAST analysis of ORF6 identified the gene as encoding a hypothetical protein; the sequence, however, did show 28.4% identity to LanY encoded within the lichenicidin operon (Begley et al., 2009). ORFs 7, 8 and 9 all encode ABC transporter related peptides, as do ORFs 11, 12 and 13. These are likely to be involved in bacteriocin immunity. ORF7 and ORF11 both encode domains resembling that of the ABC-binding cassette domain of the bacitracin-resistance transporter (cd03268) and displayed 44.5% identity to each other. Instead of the common Q-loop motif found in the nucleotide binding domains of such transporters, both these proteins instead encode an E-loop motif which is indicative of lantibiotic immunity proteins (Okuda et al., 2010, Alkhatib et al., 2012). Each of the other components encode ABC-2 type transporter domains (cl21474). The presence of

these gene clusters may suggest a dual mechanism of bacteriocin immunity. Immunity to the lichenicidin bacteriocin is thought to follow a similar mechanism, with two transporters being encoded, with one showing homology to the bacitracin transporter (Dischinger et al., 2009). Such mechanisms, however, do not confer a general immunity against all two-component lantibiotics, as both the producers of lichenicidin (*B. licheniformis* ATCC 14580) and lacticin 3147 (*Lactococcus lactis* subsp. *lactis* DPC 3147) displayed sensitivity to formicin (Table 1).

ORF10 (*frcR*), which splits the transporter clusters, encodes a LanR equivalent transcriptional regulator. This gene encodes helix-turn-helix XRE-family domains, crucial for binding DNA and regulating gene expression. This LanR type protein displayed 49.4% and 60.3% identity to the regulators found within the lichenicidin and haloduracin operons, respectively. ORF14 (*frcP*) encodes a lanthionine specific protease displaying 29.8% identity to LicP found in the lichenicidin operon. As in lichenicidin, the LanT-like ORF (*frcT*) likely cleaves the N-terminal glycine leader sequence from both propeptides upon transport, whilst the LanP-like protease (*frcP*) possibly cleaves the six newly exposed N-terminal amino acids from the β peptide to generate the mature bacteriocin (Tang et al., 2015). The final ORF found in the gene cluster encodes a DNA damage inducible protein.

Bacteriocin Structure Prediction and Analysis

The spectrum of activity and characteristics of the bacteriocin could not be determined from the crude bacteriocin supernatant alone due to the interference from the other antimicrobials produced by the strain. Thus, to determine the activity of formicin, it was necessary to purify the bacteriocin from the cell free supernatant. Using the predicted masses of the lantibiotic structural peptides identified from genomic data it was possible to determine if the formicin peptides were present in active HPLC-derived fractions using MALDI-TOF MS.

From the purified peptides, masses of 3254.34 Da and 2472.06 Da were detected for the α and β peptides, respectively. The predicted mass of the Frc α peptide based on the amino acid sequence from the genome is 3310.80 Da; the difference between the predicted and observed

masses correlates with the loss of three water residues which is most likely associated with the formation of lanthionine and methyllanthionine bridges, and also the possible formation of one disulphide bond, resulting in a predicted mass of 3254.80 Da. Due to the similarities between the two, the structure of Hal α was used as a basis for the prediction of the structure of Frc α . Based on the Hal α template the formation of a lanthionine bridge may occur between Ser-7 and Cys-17, while methyllanthionine bridges could form between Thr-18 and Cys-23, and Thr-20 and Cys-27, whilst Ser-26 remains unaltered. In addition, a disulphide bridge is also likely to form between Cys-1 and Cys-8 (Fig. 3).

The second mass determined by MALDI-TOF MS relates to the β peptide of the bacteriocin. Due to the presence of the extra LanP serine protease encoded in the bacteriocin operon and the similarity formicin displays to haloduracin and lichenicidin it is likely that the first six amino acids following the lantibiotic leader sequence are also cleaved from the formicin peptide. Once these amino acids are discounted the predicted mass of the peptide is 2614.95 Da, a difference of 142.89 Da from the mass detected by MALDI-TOF MS. This mass difference corresponds closely with the loss of 144 Da which would be associated with 8 dehydration reactions. Using the β peptides of lichenicidin and lactacin 3147 as templates, we predicted that the peptide is most likely to form bridges between Thr-1 and Cys-8, Thr-13 and Cys-17, Ser-19 and Cys-22, and Thr-23 and Cys-26. This would result in Thr-2, Ser-4, Ser-5 and Thr-10 being dehydrated to their respective Dha and Dhb residues, whilst Ser-24 remains unaltered (Fig. 3).

The purified peptides were screened against a range of indicator organisms to determine the spectrum of inhibition (Table 1). Purified formicin inhibited 29 of the 35 indicator strains screened, exhibiting a broad spectrum of activity against a range of bacterial genera including lactobacilli and enterococci, and notable pathogens such as *Staphylococcus aureus*, *Listeria monocytogenes*, *Clostridium difficile* and *Bacillus subtilis*. The Frc α peptide alone at a concentration of 50 μ M also displayed antimicrobial activity against a number of indicators, whilst Frc β alone displayed no detectable antimicrobial activity (Fig. 1d) .

In terms of thermostability, the bacteriocin retained a high degree of activity after treatment at 100°C for thirty minutes, displaying a reduction in the size of the zone of inhibition of approximately 28%. Activity was, however, lost after treatment for fifteen minutes at 121°C. The bacteriocin was also found to be susceptible to digestion by α -chymotrypsin and proteinase K, indicating its proteinaceous nature.

Homology between Bacteriocins

The previously described two-component lantibiotics all display a degree of homology with certain conserved residues found throughout. As a result, sequence comparisons of these structural peptides were carried out with formicin to determine if this conservation extended to the new bacteriocin (Fig. 4). The results indicate that formicin complies with the conservation that is seen amongst the other bacteriocins. The mersacidin like α peptides display the greatest levels of conservation, this reflects the shared mode of action in specifically binding to lipid II. This homology, especially in the lanthionine and methyllanthionine bridge forming regions, confers a structural similarity in each of the peptides. The broader role of the β peptides in membrane insertion is reflected in a greater degree of divergence in the composition of these peptides. The regions of conservation which are seen amongst the β peptides extend to Frc β also, with the C-terminus of the peptides showing a relatively conserved pattern of lanthionine and methyllanthionine bridge formation. The N-terminus of the β peptides display a much lower degree of conservation, despite this, these N-terminus regions are rich in hydrophobic amino acids which likely play an important role in membrane insertion and pore formation.

Discussion

Formicin represents a novel member of the class of two-component lantibiotics. This class of bacteriocins are themselves unusual given the lipid II binding and pore forming activities of the bacteriocin are performed by two separate peptides, whilst certain lantibiotics such as nisin and subtilin have the ability to carry out both functions on a single peptide. It is unclear as to whether these two-component lantibiotics have evolved due to a divergence of a nisin like lantibiotic into two separate genes after a duplication event or whether they have come about due to the convergence of a mersacidin like lipid II binding lantibiotic and a pore forming lantibiotic. If the latter is the case, it is interesting as to how such different peptides would have evolved to depend on each other for antibacterial activity, and in some cases lose the activity each would have shown on its own.

Sequencing of *B. paralicheniformis* APC 1576, allowed for the elucidation of the formicin bacteriocin operon (Fig. 2). Analysis of the bacteriocin operon identified two lantibiotic structural genes (*frcA1* and *frcA2*) and two modification enzymes (*frcM1* and *frcM2*) which convert the formicin structural peptides to the mature lantibiotics. Transport and leader cleavage is likely to be carried out by *frcT*, whilst *frcP* may act as a further protease, cleaving 6 N-terminal amino acids from Frc β . ORFs 7, 8, 9 and 11, 12, 13 all predict to encode ABC transporters which are likely to comprise the strain's immunity mechanism, protecting itself from attack by its own bacteriocin.

Comparative analysis of the bacteriocin structural genes allow for the homology between bacteriocins to be determined (Fig. 4). In the case of both Frc α and Frc β , the closest homologs are the haloduracin α and β mature peptides, displaying 71% and 39% identity respectively. Such homology reflects the close relationship of the two producers as both belong to the *Bacillus* genus. The differences between the formicin and lichenicidin peptides are surprisingly large, given that both are produced from related species, with the α peptides displaying 46% identity and the β peptides 36%. This would suggest that both strains may have acquired these operons independently. The

layout of the formicin operon itself differs from that of the previously characterised two-component lantibiotics, transcription of the formicin operon would appear to be unidirectional whereby the genes for the structural peptides are separated by those encoding the LanM modification enzymes, an arrangement which seems to be unique to formicin. Both the haloduracin and lichenicidin structural genes (Figure 2) would likely be transcribed in opposite directions, possibly indicating that gene inversion may have taken place. Such differences again display the evolutionary divergence seen between this class of bacteriocins.

Analysis of the primary structure of these peptides indicates that some key differences exist between the formicin peptides and other members of the class, despite such strong regions of homology found throughout. The α peptide of formicin, for example, contains only five hydrophobic amino acids, whilst others in the class contain an average of nine. Whilst hydrophobic residues are crucial for membrane activity in certain bacteriocins, it has been suggested that it is the charged residues of these lantibiotics which control binding to lipid II as opposed to hydrophobic interactions. This indicates that binding of formicin to lipid II is not compromised despite its lower hydrophobicity, a fact which is supported by the activity of the α peptide independent of the β peptide (Hsu et al., 2003, Fimland et al., 2006). As with the α peptides from enterocin W and plantaricin W, the α peptide of formicin contains six charged amino acids, with an overall positive charge of plus two, rendering them amongst the most highly charged in the class. These charged residues not only affect the structure of the peptide but the higher positive charge may lead to an increased affinity for the anionic bacterial membrane. The formicin β peptide differs most when compared to other lantibiotic β peptides with regards to charge. As is common in this class, the N-terminal tails of the β peptides are composed largely of hydrophobic residues, crucial for membrane insertion and pore formation. Whilst the previously described β peptides all contain a positively charged C-terminus, containing Lys and Arg residues, formicin is unique in that it encodes a negatively charged β peptide. The lone charged residue found in the peptide is the penultimate C-terminal Asp residue. This portion of the peptide is believed to be involved in the interaction

between the α and β peptides (Wiedemann et al., 2006), thus this negative residue may suggest an increased affinity for the positively charged α peptide, possibly representing a stronger complex compared to previously described pairs.

The tertiary structure of these peptides has an important functional role in the antimicrobial activity of these lantibiotics. Analysis of the N-terminus of Frc α suggests the formation of a disulphide bridge between Cys-1 and Cys-8. Whilst this has been shown to be inessential for antimicrobial activity, it may reduce the degradation of the peptide once secreted (Cooper et al., 2008). Of the lantibiotic rings believed to be formed in Frc α , only the C ring is thought to be essential, with alterations abolishing all activity completely in both haloduracin and lacticin 3147 (Cooper et al., 2008, Cotter et al., 2006). The B ring found in these α peptides, has been shown to be unnecessary, which is unusual given the high degree of conservation amongst such bacteriocins, including mersacidin. Disruption of the A ring in haloduracin has been shown to reduce, but not eliminate activity, thus showing this region is important but not essential for the antibacterial activity of the bacteriocin (Cooper et al., 2008). As per analysis of the haloduracin β peptide, the A ring of the peptide has been found to be dispensable, whilst loss of the C and D rings led to a reduction in activity but not total elimination. Disruption of the B ring could not be achieved without disruption of the other ring structures (Cooper et al., 2008).

Conclusion

In this study, formicin, a novel member of the class of two-component lantibiotics has been identified. Key regions of homology, primarily those involved in lanthionine and methyllanthionine bridge formation, seen throughout this class have been shown to be extended to formicin. Such homology is expected to confer a similar mode of action to all lantibiotics in this class, with the α peptide of the bacteriocin binding to lipid II and subsequently recruiting the β peptide for membrane insertion and pore formation. Whilst formicin likely conforms to such mechanisms, there are certain key variations which differentiate it from the rest of the class. The reduction of hydrophobicity of Frc α , and the unusual negative charge of Frc β make formicin a unique member of the two-component lantibiotics. Further studies are required to determine the effects of such changes on the activity of the bacteriocins, as it is recognised that charge and hydrophobicity play a central role in the activity of these lantibiotics, and in bacteriocins in general. Formicin itself displays a broad range of inhibition, inhibiting several clinically relevant Gram-positive pathogens, such as *C. difficile*, *S. aureus* and *L. monocytogenes*. With the continued progression of antibiotic resistance in pathogenic bacteria, the discovery of novel therapies against such agents is a priority and since the bacteriocin is produced by a species long associated with biotechnology applications, a straightforward route towards large scale processing of the readily purified peptides is anticipated. Thus formicin represents a potential novel antimicrobial therapy against a range of pathogenic bacteria.

Material and Methods

Isolation of Bacteria from Fish Samples

Marine fish were caught off the coast of Ireland and stored on ice prior to analysis. The intestinal contents of the fish and a sample of the skin and gills were aseptically removed. Samples were suspended in maximum recovery diluent (MRD) (Oxoid Ltd., Basingstoke, Hampshire, United Kingdom), serial dilutions were then plated on brain heart infusion (BHI) agar (Merck, Darmstadt, Germany), and marine media 2216 (Difco Laboratories, Detroit, MI) and incubated aerobically at 30°C for three days. Colonies were isolated from these plates and analysed for antimicrobial activity using deferred antagonism assays, whereby spots of the bacterial cultures were overlaid with 10 ml de Man, Rogosa and Sharpe (MRS) agar (Difco Laboratories, Detroit, MI) seeded with 25 µl of a *Lactobacillus delbrueckii* subsp. *bulgaricus* LMG 6901 overnight culture. Colonies which displayed significant zones of inhibition were further characterised.

In this study, the strain of interest, *B. paralicheniformis* APC 1576, was isolated from the intestinal tract of a mackerel (*Scomber scombrus*) and grown on BHI aerobically at 37°C. The strain was identified by 16S rRNA sequencing using the UniF (5' -AGAGTTTGATCCTGGCTCAGG- 3') and UniR (5' -ACGGCAACCTTGTTACGAGT- 3') primers to amplify the sequence. PCR products were cleaned using an illustra GFX PCR DNA and Gel Band Purification kit (GE Healthcare, Buckinghamshire, UK) and subsequent sequencing was completed by Cogenics (Essex, UK).

Colony Mass Spectrometry

Colony matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI-TOF MS) (Axima TOF² MALDI-TOF mass spectrometer, Shimadzu Biotech, Manchester, UK) was used to determine the molecular mass of the peptides produced as follows: cells were first mixed in a 70% 2-propanol 0.1% TFA (IPA) and vortexed, the sample was separated by centrifugation and the supernatant was subsequently used for analysis. A MALDI target plate was precoated with CHCA

matrix solution, 0.5 µl of the supernatant from the cell extract was then placed on the target and a final layer of matrix solution was added. Positive-ion reflectron mode was used to identify the peptide masses. The masses detected were then compared to those of known bacteriocins.

Draft Genome Sequencing

Genomic DNA was extracted using the GenElute bacterial genomic kit (Sigma-Aldrich, Wicklow, Ireland) and the Nextera XT DNA kit (Illumina, San Diego, CA, USA) was used for library preparation. The DNA was quantified using a Qubit® 2.0 fluorometer. Sequencing was performed using Illumina's MiSeq platform using paired-end 2 x 300 base pair reads in the Teagasc Sequencing Centre, Teagasc Food Research Centre Moorepark. Reads were assembled *de novo*, using SPADES (version 3.1.1), resulting in 70 contigs. Open reading frames (ORFs) were identified and annotated using Prokka (version 1.1). Further manual annotation was implemented with ARTEMIS and Artemis Comparison Tool (ACT). Genomic data is available from GenBank/EMBL under accession no. LXP000000000

Bacteriocin Identification

The bacteriocin mining tool BAGEL3 was used to identify the bacteriocin operons encoded in the genome (van Heel et al., 2013). BAGEL3 scans small ORFs to identify potential bacteriocin encoding genes. The surrounding genes are then analysed for other bacteriocin related components such as transporters and immunity proteins, thus allowing the entire bacteriocin operon to be identified (de Jong et al., 2006). The program antiSMASH was also used to identify antibiotic and secondary metabolite encoding genes within the genome, as these compounds are often associated with the *Bacillus* genus (Medema et al., 2011). Sequence alignments of the bacteriocin were performed using the Clustal Omega software.

Bacteriocin Purification

Cultures of *B. paralicheniformis* APC 1576 were grown statically overnight in 400 ml volumes of BHI broth aerobically at 37°C. The cell-free supernatant was passed through a column containing 30g

of Amberlite XAD-16 beads (Sigma-Aldrich, Wicklow, Ireland). The column was washed with 250 ml of 35% ethanol and antimicrobial activity eluted with 250ml of IPA. The IPA was removed via rotary evaporation and the sample was then applied to a 10g, 60ml Strata C₁₈-E solid-phase extraction (SPE) column (Phenomenex, Cheshire, UK). The SPE column was washed with 90ml of 35% ethanol and 90ml of IPA. The IPA was once again removed via rotary evaporation from the eluent and the sample applied to a semi prep Proteo Jupiter HPLC column (10 x 250 mm, 90Å, 4µm) running a 27.5-65% acetonitrile 0.1% TFA gradient where buffer A was 0.1% TFA and buffer B was 90% acetonitrile 0.1% TFA. Fractions were collected at 1 minute intervals and were subsequently analysed with MALDI-TOF MS and agar well diffusion assays as described below using *L. delbrueckii* subsp. *bulgaricus* LMG 6901 as the target organism to identify active fractions containing peptides of interest.

Antimicrobial Assays

The antimicrobial activity of the isolated peptides was analysed using well diffusion assays against a range of indicator organisms (Table 1). Briefly, this involved seeding 20 mls of the appropriate agar with 50µl of an overnight indicator culture, the agar was allowed to cool and 7 mm wide wells were then bored in the agar. The purified bacteriocin peptides were dried to a powder and diluted separately in potassium phosphate buffer pH 6.8 to a concentration of 50µM. The combination of these peptides in a 1:1 ratio thus gave a total bacteriocin concentration of 25µM for each peptide. Fifty microliters of this solution was then placed in wells in the indicator plate, these were subsequently incubated overnight under the appropriate growth conditions as outlined in Table 1.

Peptide Stability

The stability of the bacteriocin was determined using purified peptides. To determine the active temperature range of the lantibiotic, 25µM aliquots of the bacteriocin were treated at 60°C, 70°C, 80°C, 90°C and 100°C for 30 minutes, a sample was also treated at 121°C for 15 minutes. These samples were then tested for inhibitory activity against *L. delbrueckii* subsp. *bulgaricus* LMG 6901 in

well diffusion assays as previously described. To determine the susceptibility of the bacteriocin to proteases, 5 μ M aliquots of the α and β peptides were treated separately with proteinase K and α -chymotrypsin each at a concentration of 10 mg/ml (Sigma-Aldrich, Wicklow, Ireland). Samples were incubated at 37°C for three hours followed by treatment at 100°C for ten minutes to inactivate these proteases. Both bacteriocin peptides were then combined post treatment to give a final total concentration of 2.5 μ M, these were then screened against *L. delbrueckii* subsp. *bulgarcus* LMG 6901 in well diffusion assays to determine the antimicrobial activity.

Figures and Tables

Figure 1. Formicin identification and activity. (a) Deferred antagonism assay against *L. delbrueckii* subsp. *bulgaricus* LMG 6901 identified *B. licheniformis* APC 1576 as an antimicrobial producer. (b) Antibacterial activity of the *B. licheniformis* APC 1576 cell free supernatant against *L. delbrueckii* subsp. *bulgaricus* LMG 6901 in a well diffusion assay. (c) Colony MALDI-TOF MS displaying the masses of the peptides produced by *B. licheniformis* APC 1576, allowing identification of the antimicrobials produced (3255.92 Da = Frc α (formicin); Frc β is not seen using colony MALDI-TOF MS; 1423.94 Da = Bacitracin). (d) Combined and individual activity of purified formicin peptides.

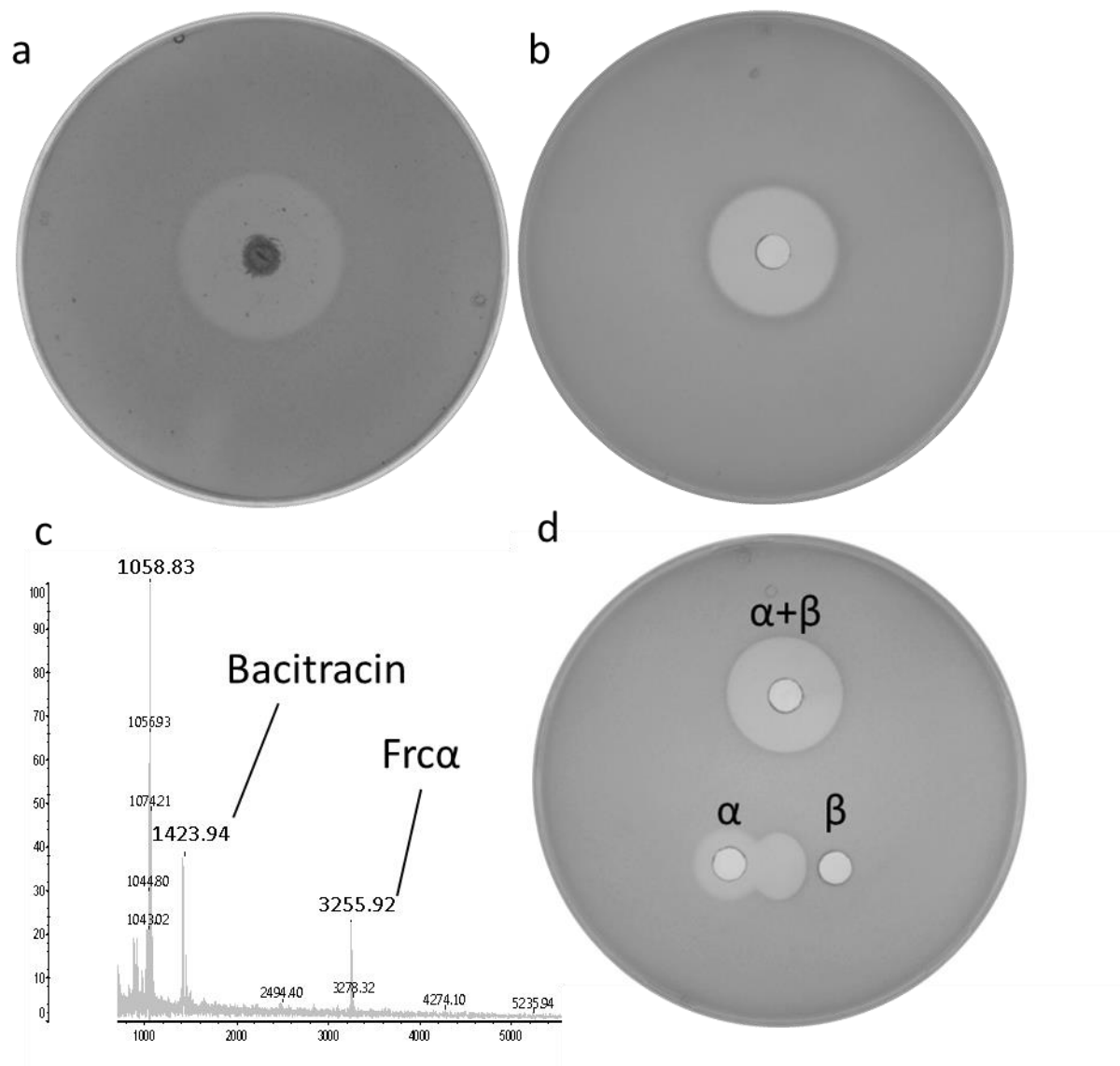


Figure 2. Formicin Operon. Visualisation of the formicin, lichenicidin and haloduracin bacteriocin gene clusters. Clear bacteriocin homologs are identified using the accepted nomenclature for describing lantibiotics. For formicin, *frcA1* and *frcA2* encode the putative bacteriocins, *frcM1* and *frcM2* encode the accompanying modification enzymes and *frcT* and *frcP* are involved in bacteriocin transport and leader cleavage. Similar nomenclature is used for lichenicidin (*lic*) and haloduracin (*hal*) genes. Genes are colour-coded as per BAGEL3, indicating the putative role of each protein.

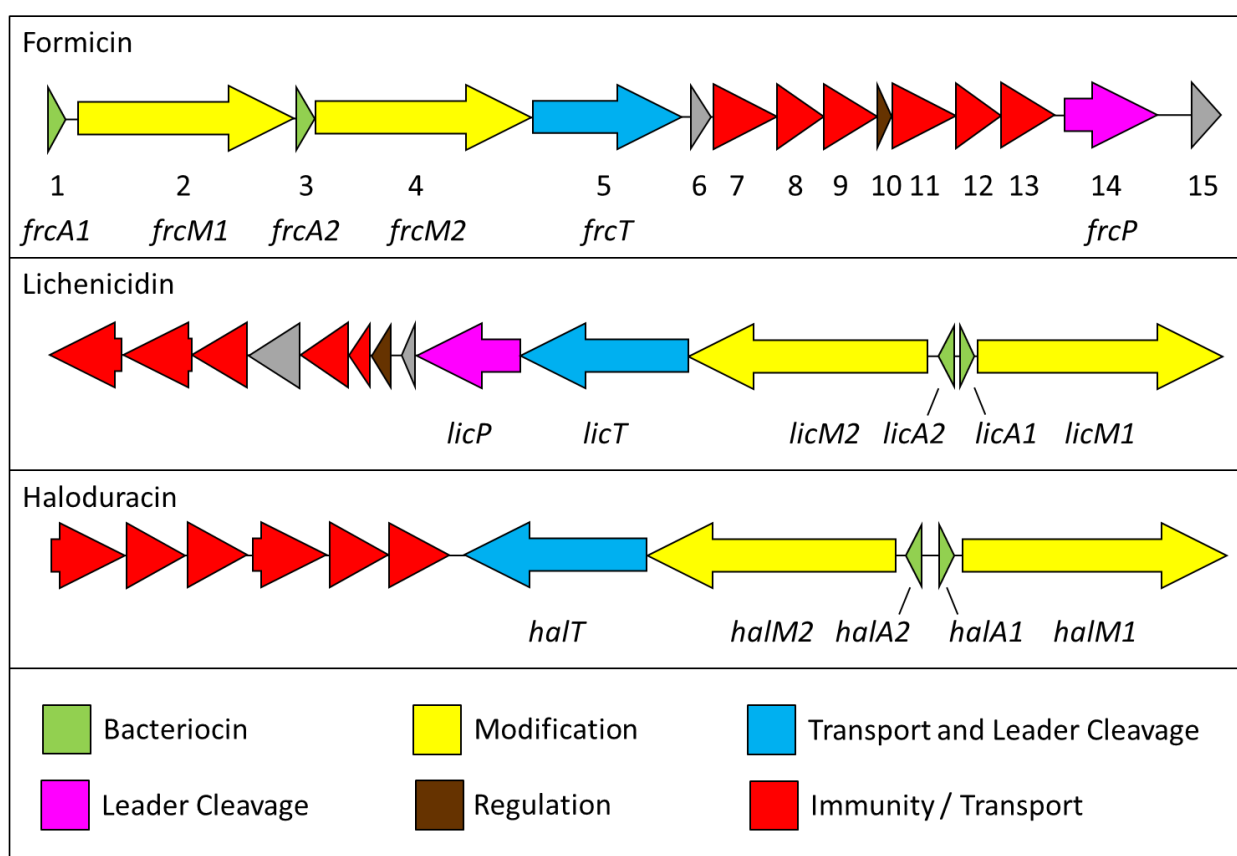
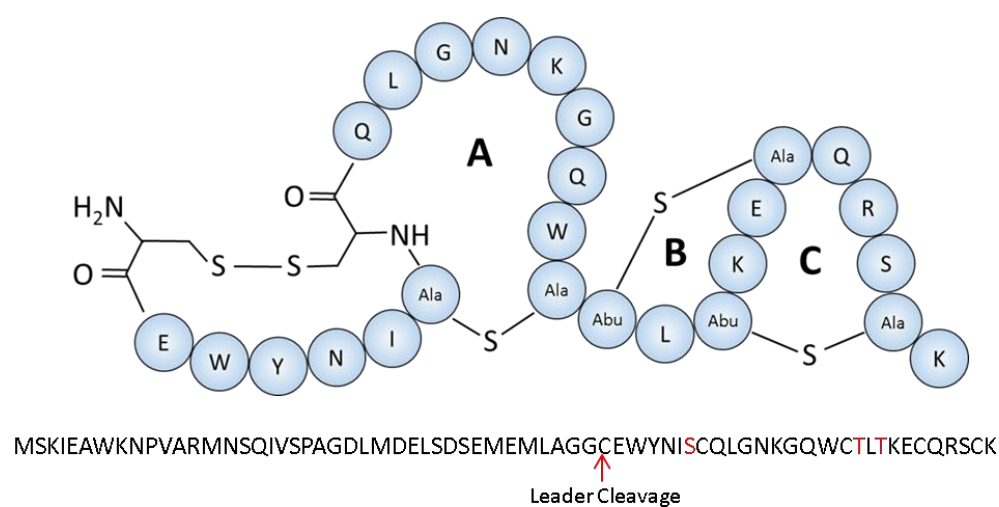
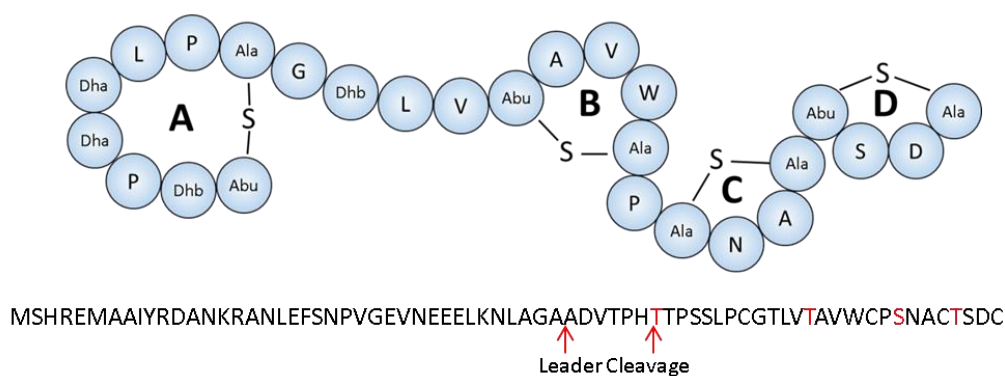


Figure 3. Lantibiotic Structure Prediction. The structures of the formicin α and β peptides were predicted using the Hal α and Lic β peptides, respectively, as templates. The conservation of key amino acids suggests a structural homology between the peptides. The rings formed from lanthionine and methyllanthionine bridges are labelled alphabetically, with the N-terminal ring of Frca excluded as it is predicted to be formed via a disulphide bond. The bacteriocin prepropeptides are shown below each structure, with likely dehydrated serine and threonine residues indicated in red.



Frca



Frc β

Figure 4. Sequence Alignment of Formicin Structural Peptides. Using Clustal Omega, the formicin peptides FrcA1 (a) and FrcA2 (b) were aligned against the previously described two-component bacteriocins. The percentage amino acid identities of each peptide with the formicin peptides are shown. The conservation score between the peptides were calculated with Clustal Omega for the alignments containing less than 25% gaps, * represent a score of 10. The sequences in bold represent the six amino acids cleaved from the N-terminus of these peptides by LanP proteases.

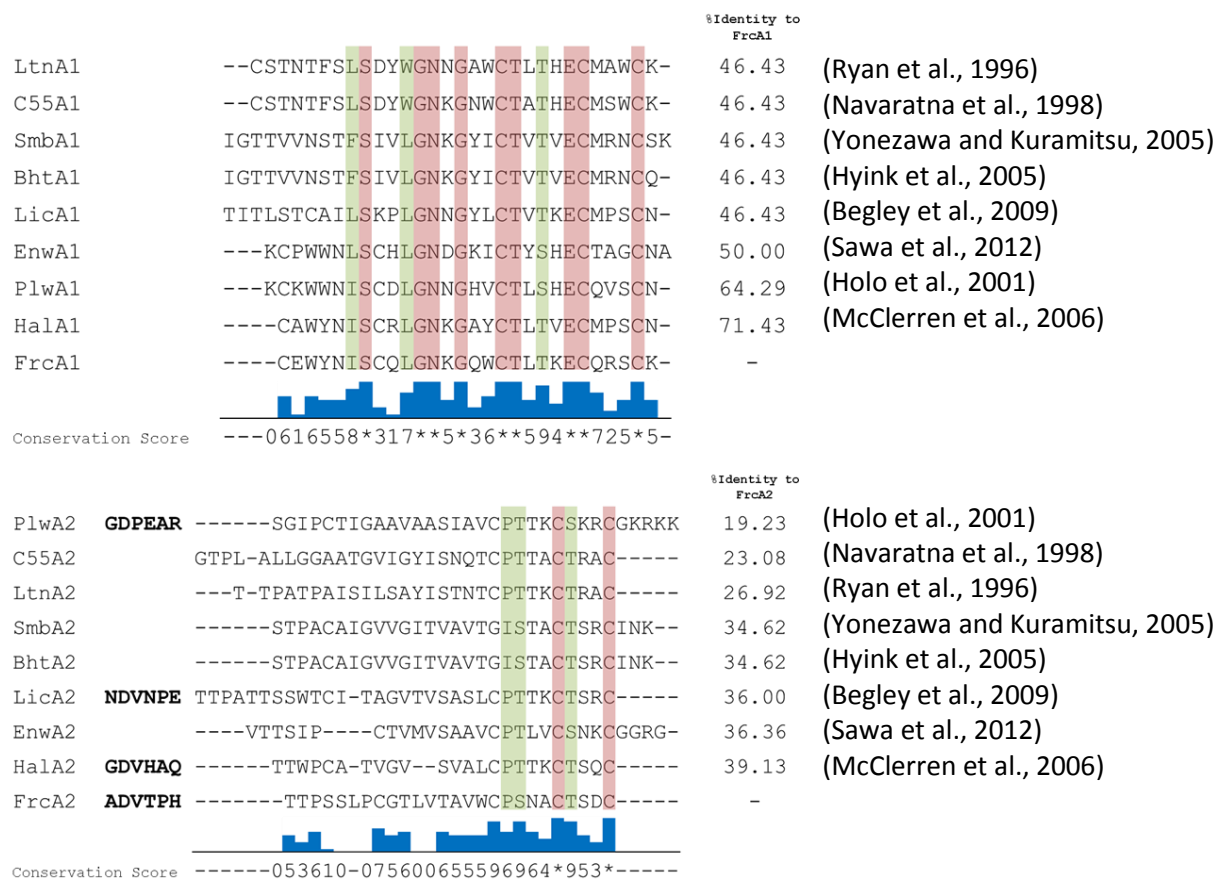


Table 1. Growth conditions of indicator strains and inhibition spectrum of formicin pure peptides following well diffusion assays (- = No activity, + = 0.5-1.5mm inhibition zone, ++ = 2-3.5mm inhibition zone, +++ = \geq 4mm inhibition zone).

Species	Strain	Growth Conditions			
		Temp (°C)	Atmosphere	Growth Media	Inhibition
<i>Lactobacillus delbrueckii</i> subsp. <i>bulgaricus</i>	LMG 6901	37	Anaerobic	MRS	+++
<i>L. delbrueckii</i> subsp. <i>lactis</i>	LMG 7942	37	Anaerobic	MRS	+++
<i>L. amylovorus</i>	LMG 9496	37	Anaerobic	MRS	+
<i>L. fermentum</i>	LMG 6902	37	Anaerobic	MRS	++
<i>L. agilis</i>	LMG 9186	37	Anaerobic	MRS	++
<i>L. casei</i>	LMG 6904	37	Anaerobic	MRS	++
<i>L. amylophilus</i>	DSM 20533	37	Anaerobic	MRS	+++
<i>L. acidophilus</i>	LMG 9433	37	Anaerobic	MRS	-
<i>L. buchneri</i>	DSM 20057	37	Anaerobic	MRS	-
<i>Enterococcus faecium</i>	DPC 4898	37	Anaerobic	MRS	++
<i>E. faecalis</i>	LMG7397	37	Anaerobic	MRS	++
<i>E. saccharolyticus</i>	DPC 4902	37	Anaerobic	MRS	++
<i>E. mundtii</i>	LMG 10748	37	Anaerobic	MRS	+
<i>Lactococcus lactis</i>	HP	30	Aerobic	LM17	+++
<i>L. lactis</i> subsp. <i>lactis</i>	DPC 3147	30	Aerobic	LM17	+++
<i>Micrococcus luteus</i>	DPC 6275	30	Aerobic	BHI	+++
<i>Listeria innocua</i>	DPC 3572	37	Aerobic	BHI	++
<i>L. monocytogenes</i>	DPC 5788	37	Aerobic	BHI	+
<i>L. monocytogenes</i>	DPC 6893	37	Aerobic	BHI	+
<i>L. monocytogenes</i>	DPC 6894	37	Aerobic	BHI	+
<i>Bacillus cereus</i>	DPC 6087	37	Aerobic	BHI	+
<i>B. subtilis</i>	DPC 6551	37	Aerobic	BHI	++
<i>B. subtilis</i>	LMG 8198	37	Aerobic	BHI	+
<i>B. licheniformis</i>	DSM 13	37	Aerobic	BHI	++
<i>Pseudomonas aeruginosa</i>	APC 2064	37	Aerobic	BHI	-
<i>Staphylococcus chromogenes</i>	APC 82	37	Aerobic	BHI	-
<i>S. aureus</i>	C55	37	Aerobic	BHI	-
<i>S. aureus</i>	R963	37	Aerobic	BHI	+
<i>Streptococcus mutans</i>	APC 1076	37	Aerobic	BHI	+++
<i>Clostridium indolis</i>	DPC 6345	37	Anaerobic	RCM	++
<i>C. histolyticum</i>	DPC 6344	37	Anaerobic	RCM	++
<i>C. sporogenes</i>	DPC 6341	37	Anaerobic	RCM	++
<i>C. difficile</i>	ATCC 1382	37	Anaerobic	RCM	+
<i>C. perfringens</i>	LMG 11264	37	Anaerobic	RCM	++
<i>Salmonella enterica</i>	APC 174	37	Aerobic	BHI	-

References

- ALKHATIB, Z., ABTS, A., MAVARO, A., SCHMITT, L. & SMITS, S. H. 2012. Lantibiotics: how do producers become self-protected? *J Biotechnol*, 159, 145-54.
- BEGLEY, M., COTTER, P. D., HILL, C. & ROSS, R. P. 2009. Identification of a Novel Two-Peptide Lantibiotic, Lichenicidin, following Rational Genome Mining for LanM Proteins. *Applied and Environmental Microbiology*, 75, 5451-5460.
- CHATTERJEE, S., CHATTERJEE, S., LAD, S. J., PHANSALKAR, M. S., RUPP, R. H., GANGULI, B. N., FEHLHABER, H. W. & KOGLER, H. 1992. Mersacidin, a new antibiotic from *Bacillus*. Fermentation, isolation, purification and chemical characterization. *J Antibiot (Tokyo)*, 45, 832-8.
- COOPER, L. E., MCCLERREN, A. L., CHARY, A. & VAN DER DONK, W. A. 2008. Structure-activity relationship studies of the two-component lantibiotic haloduracin. *Chem Biol*, 15, 1035-45.
- COTTER, P. D., DEEGAN, L. H., LAWTON, E. M., DRAPER, L. A., O'CONNOR, P. M., HILL, C. & ROSS, R. P. 2006. Complete alanine scanning of the two-component lantibiotic lactacin 3147: generating a blueprint for rational drug design. *Mol Microbiol*, 62, 735-47.
- COTTER, P. D., ROSS, R. P. & HILL, C. 2013. Bacteriocins - a viable alternative to antibiotics? *Nature Reviews Microbiology*, 11, 95-105.
- DE JONG, A., VAN HIJUM, S. A. F. T., BIJLSMA, J. J. E., KOK, J. & KUIPERS, O. P. 2006. BAGEL: a web-based bacteriocin genome mining tool. *Nucleic Acids Research*, 34, W273-W279.
- DISCHINGER, J., JOSTEN, M., SZEKAT, C., SAHL, H. G. & BIERBAUM, G. 2009. Production of the novel two-peptide lantibiotic lichenicidin by *Bacillus licheniformis* DSM 13. *PLoS One*, 4, e6788.
- ESCANO, J., STAUFFER, B., BRENNAN, J., BULLOCK, M. & SMITH, L. 2015. Biosynthesis and transport of the lantibiotic mutacin 1140 produced by *Streptococcus mutans*. *J Bacteriol*, 197, 1173-84.
- FIMLAND, G., PIRNESKOSKI, J., KAEWSRICHAN, J., JUTILA, A., KRISTIANSEN, P. E., KINNUNEN, P. K. & NISSEN-MEYER, J. 2006. Mutational analysis and membrane-interactions of the β -sheet-like N-terminal domain of the pediocin-like antimicrobial peptide sakacin P. *Biochimica et Biophysica Acta (BBA)-Proteins and Proteomics*, 1764, 1132-1140.
- FURGERSON IHNKEN, L. A., CHATTERJEE, C. & VAN DER DONK, W. A. 2008. In vitro reconstitution and substrate specificity of a lantibiotic protease. *Biochemistry*, 47, 7352-63.
- GILLOR, O., NIGRO, L. M. & RILEY, M. A. 2005. Genetically engineered bacteriocins and their potential as the next generation of antimicrobials. *Curr Pharm Des*, 11, 1067-75.
- HOLO, H., JEKNIC, Z., DAESCHEL, M., STEVANOVIC, S. & NES, I. F. 2001. Plantaricin W from *Lactobacillus plantarum* belongs to a new family of two-peptide lantibiotics. *Microbiology*, 147, 643-51.
- HSU, S. T., BREUKINK, E., BIERBAUM, G., SAHL, H. G., DE KRUIJFF, B., KAPTEIN, R., VAN NULAND, N. A. & BONVIN, A. M. 2003. NMR study of mersacidin and lipid II interaction in dodecylphosphocholine micelles. Conformational changes are a key to antimicrobial activity. *J Biol Chem*, 278, 13110-7.
- HYINK, O., BALAKRISHNAN, M. & TAGG, J. R. 2005. *Streptococcus rattus* strain BHT produces both a class I two-component lantibiotic and a class II bacteriocin. *FEMS Microbiol Lett*, 252, 235-41.
- KATZ, E. & DEMAINE, A. L. 1977. The peptide antibiotics of *Bacillus*: chemistry, biogenesis, and possible functions. *Bacteriol Rev*, 41, 449-74.
- LEE, J. H., LI, X. & O'SULLIVAN, D. J. 2011. Transcription analysis of a lantibiotic gene cluster from *Bifidobacterium longum* DJO10A. *Appl Environ Microbiol*, 77, 5879-87.
- MARTIN, N. I., SPRULES, T., CARPENTER, M. R., COTTER, P. D., HILL, C., ROSS, R. P. & VEDERAS, J. C. 2004. Structural characterization of lactacin 3147, a two-peptide lantibiotic with synergistic activity. *Biochemistry*, 43, 3049-56.

- MCCLERREN, A. L., COOPER, L. E., QUAN, C., THOMAS, P. M., KELLEHER, N. L. & VAN DER DONK, W. A. 2006. Discovery and in vitro biosynthesis of haloduracin, a two-component lantibiotic. *Proceedings of the National Academy of Sciences of the USA*, 103, 17243-8.
- MEDEMA, M. H., BLIN, K., CIMERMANCIC, P., DE JAGER, V., ZAKRZEWSKI, P., FISCHBACH, M. A., WEBER, T., TAKANO, E. & BREITLING, R. 2011. antiSMASH: rapid identification, annotation and analysis of secondary metabolite biosynthesis gene clusters in bacterial and fungal genome sequences. *Nucleic Acids Res*, 39, W339-46.
- NAVARATNA, M. A., SAHL, H. G. & TAGG, J. R. 1998. Two-component anti-Staphylococcus aureus lantibiotic activity produced by Staphylococcus aureus C55. *Appl Environ Microbiol*, 64, 4803-8.
- OKUDA, K., YANAGIHARA, S., SUGAYAMA, T., ZENDO, T., NAKAYAMA, J. & SONOMOTO, K. 2010. Functional significance of the E loop, a novel motif conserved in the lantibiotic immunity ATP-binding cassette transport systems. *J Bacteriol*, 192, 2801-8.
- REA, M. C., DOBSON, A., O'SULLIVAN, O., CRISPIE, F., FOUHY, F., COTTER, P. D., SHANAHAN, F., KIELY, B., HILL, C. & ROSS, R. P. 2011. Effect of broad- and narrow-spectrum antimicrobials on Clostridium difficile and microbial diversity in a model of the distal colon. *Proc Natl Acad Sci U S A*, 108 Suppl 1, 4639-44.
- REA, M. C., SIT, C. S., CLAYTON, E., O'CONNOR, P. M., WHITTAL, R. M., ZHENG, J., VEDERAS, J. C., ROSS, R. P. & HILL, C. 2010. Thuricin CD, a posttranslationally modified bacteriocin with a narrow spectrum of activity against Clostridium difficile. *Proceedings of the National Academy of Sciences USA*. United States.
- ROGERS, L. A. 1928. The Inhibiting Effect of Streptococcus lactis on Lactobacillus bulgaricus. *J Bacteriol*, 16, 321-5.
- RYAN, M. P., REA, M. C., HILL, C. & ROSS, R. P. 1996. An application in cheddar cheese manufacture for a strain of Lactococcus lactis producing a novel broad-spectrum bacteriocin, lacticin 3147. *Applied and Environmental Microbiology*, 62, 612-619.
- SAWA, N., WILAI PUN, P., KINOSHITA, S., ZENDO, T., LEELAWATCHARAMAS, V., NAKAYAMA, J. & SONOMOTO, K. 2012. Isolation and characterization of enterocin W, a novel two-peptide lantibiotic produced by Enterococcus faecalis NKR-4-1. *Appl Environ Microbiol*, 78, 900-3.
- STEIN, T., HEINZMANN, S., DUSTERHUS, S., BORCHERT, S. & ENTIAN, K. D. 2005. Expression and functional analysis of the subtilin immunity genes spaIFEG in the subtilin-sensitive host Bacillus subtilis MO1099. *J Bacteriol*, 187, 822-8.
- TAKALA, T. M., KOPONEN, O., QIAO, M. & SARIS, P. E. J. 2004. Lipid-free NisI: interaction with nisin and contribution to nisin immunity via secretion. *FEMS Microbiology Letters*, 237, 171-177.
- TANG, W., DONG, S.-H., REPKA, L. M., HE, C., NAIR, S. K. & VAN DER DONK, W. A. 2015. Applications of the class II lanthipeptide protease LicP for sequence-specific, traceless peptide bond cleavage. *Chemical Science*, 6, 6270-6279.
- VAN HEEL, A. J., DE JONG, A., MONTALBAN-LOPEZ, M., KOK, J. & KUIPERS, O. P. 2013. BAGEL3: Automated identification of genes encoding bacteriocins and (non-)bactericidal posttranslationally modified peptides. *Nucleic Acids Res*, 41, W448-53.
- WIEDEMANN, I., BOTTIGER, T., BONELLI, R. R., WIESE, A., HAGGE, S. O., GUTSMANN, T., SEYDEL, U., DEEGAN, L., HILL, C., ROSS, P. & SAHL, H. G. 2006. The mode of action of the lantibiotic lacticin 3147--a complex mechanism involving specific interaction of two peptides and the cell wall precursor lipid II. *Mol Microbiol*, 61, 285-96.
- WILLEY, J. M. & VAN DER DONK, W. A. 2007. Lantibiotics: peptides of diverse structure and function. *Annu Rev Microbiol*, 61, 477-501.
- XIE, L. & VAN DER DONK, W. A. 2004. Post-translational modifications during lantibiotic biosynthesis. *Current Opinion in Chemical Biology*, 8, 498-507.
- YONEZAWA, H. & KURAMITSU, H. K. 2005. Genetic analysis of a unique bacteriocin, Smb, produced by Streptococcus mutans GS5. *Antimicrob Agents Chemother*, 49, 541-8.

Chapter 3: Bacteriocin Gene-Trait matching across the complete *Lactobacillus* Pan- genome.

Mass spectrometry and peptide purification was carried out by Ms. Paula O'Connor, initial BAGEL screen was carried out by Dr. Orla O'Sullivan

Abstract

Lactobacilli constitute a large genus of Gram-positive lactic acid bacteria which have widespread roles, ranging from gut commensals to starters in fermented foods. A combination of *in silico* and laboratory-based screening allowed us to determine the overall bacteriocin producing potential of representative strains of each species of the genus. The genomes of 175 lactobacilli and 38 associated species were screened for the presence of antimicrobial producing genes and combined with screening for antimicrobial activity against a range of indicators. There also appears to be a link between the strains environment and bacteriocin production, with those from the animal and human microbiota encoding over twice as many bacteriocins as those from other sources. Five novel bacteriocins were identified belonging to differing bacteriocin classes, including two-peptide bacteriocins (muricidin and acidocin X) and circular bacteriocins (paracyclisin). In addition, there was a clear clustering of helveticin type bacteriolysins in the *Lactobacillus acidophilus* group of species. This combined *in silico* and *in vitro* approach to screening has demonstrated the true diversity and complexity of bacteriocins across the genus. It also highlights their biological importance in terms of communication and competition between closely related strains in diverse complex microbial environments.

Introduction

Bacteriocins are ribosomally-synthesised antimicrobial peptides which generally act by inducing pore formation or inhibiting cell wall synthesis in target cells (Cotter et al., 2005). Some bacteriocins, such as nisin, have found widespread applicability as bio preservatives in food systems where they have been used for decades. Moreover, bacteriocin production can also be a key probiotic trait (Dobson et al., 2012, Walsh et al., 2008), and bacteriocins have been suggested as potential alternatives to antibiotics in the future (Cotter et al., 2013). The *Lactobacillus* genus has a long association with bacteriocin production, with numerous bacteriocins isolated from such species (O'Shea et al., 2013, Holo et al., 2001). Originally bacteriocin producers were isolated from functional screens against selected target strains, but many studies now rely on prior *in silico* screening, using tools such as BAGEL (Begley et al., 2009, McClarren et al., 2006). BAGEL scans the bacterial genome for putative bacteriocin open reading frames (ORFs) and also analyses surrounding ORFs to search for possible biosynthetic genes, immunity genes and transporters (de Jong et al., 2010). Whilst the areas of interest identified by BAGEL represent potential bacteriocin operons, this does not always translate into functional bacteriocin production for many reasons including problems with mutation, regulation or target specificity.

There are varying accounts on the extent of bacteriocin production in the environment. While numerous accounts assume ubiquity in production (Gillor et al., 2008, Inglis et al., 2013), a definitive analysis has yet to focus on clarifying the actual extent of bacteriocin production. In this study, we elucidate the bacteriocinogenic potential of representative species of the *Lactobacillus* genus and some related genera; i.e. the *Lactobacillus* Genus Complex. Previously Sun *et al.* (Sun et al., 2015) analysed the genomes of 175 *Lactobacillus* species and 38 closely related species, carrying out a screen for putative bacteriocin operons using the BAGEL bacteriocin mining tool. Despite no longer formally being considered as bacteriocins, large (>30kDa) helveticin-like antimicrobial proteins were also included in the study. Based on those results, we analysed strains which were identified as

encoding putative bacteriocin operons for *in vitro* production using well diffusion assays (WDAs) and MALDI TOF MS. Well diffusion assays were used to detect antimicrobial production whilst MALDI TOF MS and SDS PAGE were used to identify the masses of the bacteriocins. Peptide masses identified by MS were correlated with the theoretical masses of bacteriocins identified by BAGEL to confirm the identity of the anti-microbial. We reinforced the BAGEL results with BLAST searches for key lantibiotic and sactibiotic enzymes using specific sequences employed in previous studies against this new dataset of *Lactobacillus* genomes (Begley et al., 2009, Marsh et al., 2010, Goto et al., 2010). This redundancy allows for a more comprehensive analysis of bacteriocin gene clusters in the sequenced strains.

Results

Distribution of Bacteriocin Operons

Several studies have completed bacteriocin screens on diverse and unrelated species of bacteria (Begley et al., 2009, Walsh et al., 2015, Murphy et al., 2011). The aim of this study was to focus primarily on the lactobacilli and investigate the distribution of bacteriocin genes across this single large important genus. From the information identified by BAGEL, we used a phylogenetic tree to visualise the distribution of bacteriocin operons within the genus (Figure 1). Historically the *Lactobacillus* genus has a long association with bacteriocin production. While this study focuses on the type strain of each *Lactobacillus* species, Table 1 identifies those bacteriocins which have been previously identified and characterised from all strains in the *Lactobacillus* Genus Complex. In all, 66 bacteriocins have been characterised from lactobacilli previously, which would suggest a high degree of production within the genus. It is notable that the production of these unique bacteriocins is, in fact, restricted to 16 different species.

Visualisation of the distribution of bacteriocins throughout the *Lactobacillus* Genus Complex shows that there is a clear clustering of helveticin-like operons amongst the *L. acidophilus* branch of species, indicating that such genes have been retained from a common ancestor (Figure 1). Despite being previously classified as class III bacteriocins, these proteins are now termed bacteriolysins and are considered a distinct group of antimicrobials. Whilst these proteins are ribosomally synthesised, they are much larger than classical Gram positive bacteriocins (approx.30 kDa) and are heat labile. Helveticin J is the only previously characterised bacteriolysin from lactobacilli (Joerger and Klaenhammer, 1986), but here we show that these genes are actually highly prevalent across the genus, with 43 potential homologs identified from 23 strains (for alignment results see Supplementary Figure 1). Of the 18 strains in the *L. acidophilus* group, 36 helveticin homologs were distributed amongst 16 of these strains. While certain strains can encode up to four helveticin homologs, there is insufficient homology between those to suggest recent gene duplications. The

high degree of homology (in some cases greater than 99%) between some structural genes encoded by different strains does indicate that horizontal gene transfer of helveticin homologs has occurred; such a mechanism may also explain the presence of these genes in the six strains outside of the *L. acidophilus* group (Figure 1).

The environment from which these strains have been isolated also seems to correlate with their bacteriocinogenic potential (Supplementary Table 1). For example, of the strains isolated from an animal or human origin 37.5% were identified as encoding a complete bacteriocin or helveticin like operon in BAGEL or BLAST screens (21 of 56 strains). This figure for strains isolated from non-animal source (food, plants, environmental and alcohol/wine products) displays an over two-fold reduction at 16.67% (25 of 150 strains). This result suggests that the bacteriocin production may prove to be a competitive advantage for strains from complex environments such as the microbiota of humans and animals.

Diversity of Bacteriocins Identified

Bacteriocins are a diverse and varied group of antimicrobials, which use different systems for bacteriocin modification, transport and immunity. *In silico* analysis allows us to determine which types of bacteriocins the lactobacilli can synthesise. To analyse the diversity of the bacteriocins encoded by lactobacilli, an *in silico* screen was first carried out on the genome of each strain followed by *in vitro* screening of each bacteriocin encoding strain to identify antimicrobial activity against a range of indicators (Table 2). MALDI TOF MS and SDS PAGE allowed us to determine the mass and subsequently the identity of the bacteriocins produced by the strains (Supplementary Figure 2). The bacteriocin classification scheme devised by Cotter *et al.* (Cotter et al., 2005, Cotter et al., 2013) was used to distinguish between the different classes of bacteriocins.

Class I

Class I bacteriocins are comprised of ribosomally synthesised, post-translationally modified bacteriocins (RiPPs)(Cotter et al., 2013). Originally restricted to lantibiotics, this class has now been extended to include other post-translationally modified bacteriocins such as sactibiotics.

Lantibiotics

Lantibiotics are a group of bacteriocins characterised by the presence of lanthionine and methyllanthionine bridges. Here, serine and threonine residues are converted to 2,3-didehydroalanine (Dha) and 2,3-didehydrobutyrine (Dhb), respectively, which then react with the thiol group found in cysteine residues, forming lanthionine or methyllanthionine thioether cross-links (McAuliffe et al., 2001). Currently three lantibiotics have been attributed to the *Lactobacillus* genus; lactocin S (Mortvedt et al., 1991), plantaricin C (Gonzalez et al., 1994) and the two peptide lantibiotic plantaricin W (Holo et al., 2001).

The BAGEL screen of the *Lactobacillus* dataset identified three further lactobacilli encoding lantibiotic structural peptides (Table 3). Of these, potential production was only identified in *L. taiwanensis* DSM 21401 which encodes a type I lantipeptide (a lantibiotic which doesn't display antimicrobial activity), characterised by the presence of LanB and LanC modification enzymes. What is unusual about this peptide is the fact the structural gene is small compared to other lantipeptides, with the mature peptide predicted to contain only 14 amino acids. Despite a lack of demonstrated antibacterial activity against the range of indicators tested, MALDI TOF MS did identify a mass which correlates with the predicted mass of the mature lantipeptide. The lack of antimicrobial activity may simply imply that the indicator organisms tested were not sensitive, or that the putative lantipeptide has a signalling rather than a bacteriocidal role.

A further type I lantibiotic operon was identified by BAGEL in the strain *L. amylovorus* DSM 20531. This strain appears to encode a complete lantibiotic operon which contains the required modification enzymes and an ABC transporter. *L. gastricus* DSM 16045 was found to encode a Lan C

homolog but a LanB homolog was absent from the operon which is necessary for initial dehydration of serine and threonine residues. The production of either of these bacteriocins was not detected *in vitro*.

Lantibiotic operons were also identified in some of the other genera studied. *Pediococcus damnosus* DSM 20331 was found to encode and produce a class II lantibiotic. This strain has previously been found to produce the partially characterised lantibiotic pediocin PD-1 (Bauer et al., 2005). From genomic data used in this study, the sequence of the pediocin PD-1 gene has now been elucidated, showing a high similarity to the lantibiotic plantaricin C (PlnC) (Turner et al., 1999). Due to the similarity between the two bacteriocins, pediocin PD-1 likely shares a common mode of action with PlnC whose activity has been shown to be as a result of the combination of pore formation and inhibition of lipid II synthesis (Wiedemann et al., 2006). *P. claussenii* DSM 14800 was also shown to encode pediocin PD-1, however, this strain failed to display bacteriocin production. The *Carnobacterium maltaromaticum* strains DSM 20722 and DSM 20730 were also both found to encode the two-component lantibiotic carnolysin, however the *in vitro* production of this bacteriocin was not seen in either strain (Tulini et al., 2014).

To supplement the results of BAGEL searches, previous *in silico* lantibiotic screens were repeated on the new *Lactobacillus* dataset. We used the modification enzymes NisC, LtnM1 and VenL as drivers in the BLAST search for novel lantibiotics (Marsh et al., 2010, Begley et al., 2009, Goto et al., 2010). *L. gallinarum* DSM 10532, *L. crispatus* DSM 20584 and *P. cellicola* DSM 17757 were all found to harbour a NisC homolog, despite not being identified by BAGEL. However, upon examination of the surrounding genes, no potential structural genes were identified. Strains identified in BLAST searches as encoding LanM homologs had also been identified by BAGEL. No homolog of the novel lanthionine synthase VenL was identified in the BLAST screen.

Sactibiotics

The sactibiotics are a growing class of bacteriocins characterised by the presence of unusual sulphur to α -carbon linkages. These modifications are carried out by radical S-adenosylmethionine (SAM) proteins which catalyse the formation of these thioether bonds (Fluhe et al., 2012, Mathur et al., 2015). To analyse the prevalence of potential sactibiotic operons within the lactobacilli, the sequences for the radical SAMs associated with a two-component sactibiotic thuricin CD (TrnC and TrnD) were used as drivers in a BLAST analysis of the genomes available (Rea et al., 2010, Murphy et al., 2011). Only two radical SAMs were found resembling those associated with thuricin CD. *L. mali* DSM 20444 was found to encode one such SAM, however, analysis of the operon failed to identify a potential structural gene. *Kandleria vitulina* DSM 20405 appears to encode a complete sactibiotic operon, encompassing a structural gene, transporter and associated radical SAM, however, no biological activity could be attributed to this strain with the panel of indicators tested. BAGEL further identified two potential sactibiotic related radical SAM proteins in *C. maltaromaticum* DSM 20342 and DSM 20722 but no potential structural genes for these enzymes were apparent.

TOMMs

Thiazole/oxazole modified microcins (TOMMs) are a class of RiPPs which are now included with the class I bacteriocins. These peptides undergo extensive post-translational modification, where cysteine, serine and threonine residues are converted into the corresponding heterocycles; thiazole, oxazole and methyloxazole, respectively (Molloy et al., 2011). TOMMs exist in gene clusters, with components encoding several factors involved in transport, modification and immunity. Using streptolysin as an example, the modification of the structural peptide is the result of the activity of the SagBCD enzyme complex, encompassing a cyclodehydratase (SagC), a dehydrogenase (SagB) and a docking protein (SagD) (Lee et al., 2008). Whilst SagBCD clusters are described as being relatively widespread amongst prokaryotes, no TOMM has yet been identified from a *Lactobacillus* species (Lee et al., 2008). In our study *L. crispatus* DSM 20584, *L. intestinalis* DSM 6629 and *Oenococcus kitaharae* DSM 17330 were identified by BAGEL as encoding homologs of the SagBCD gene cluster.

Whilst the operons in *O. kitaharae* DSM 17330 and *L. intestinalis* DSM 6629 appear to be complete, the *L. crispatus* DSM 20584 TOMM operon appears to lack a structural gene, however, the structural gene for similar operons has been found to be some distance from the SagBCD homologs previously (Haft, 2009). Of these three strains, *L. crispatus* DSM 20584 was the only one found to display antimicrobial activity; the source of this activity, however, remains unclear.

Class II

Class II bacteriocins are small heat stable peptides which are not subject to extensive post translational modification, most of which act to permeabilize the membrane of target cells (Cotter et al., 2005). This class of bacteriocins is further subdivided based on the structure and activity of the peptides.

Class IIa

Class IIa or 'pediocin-like' bacteriocins display a narrow range of antimicrobial activity, particularly displaying strong anti-listerial activity. Such bacteriocins encompass a highly conserved YGNGV/L N-terminal motif followed by cysteine residues which can form a disulphide bridge. Unlike the N-terminus, the C-terminus is less conserved and is likely involved in membrane insertion and pore formation (Fimland et al., 2005). These bacteriocins likely act by using the mannose-phosphotransferase system on sensitive cells as a receptor (Ramnath et al., 2000).

Despite having a long association with this class of bacteriocins, surprisingly only 3 *Lactobacillus* strains were found to encode what appear to be complete class IIa bacteriocin operons, containing structural, immunity and transport genes (Table 4a). Of these, *L. hordei* DSM 19519 displayed bacteriocin production against six of the indicators tested. From MALDI TOF MS and BAGEL results, the production of coagulin was confirmed. This 44 amino acid bacteriocin was originally isolated from *Bacillus coagulans* and closely resembles the bacteriocin pediocin PA-1, differing by a single amino acid due to a N41T substitution (Hyronimus et al., 1998, Le Marrec et al., 2000). The presence of a further pediocin-like operon was noted within the *L. hordei* genome,

encoding a structural peptide displaying 74% amino acid identity to plantaricin 423. Production of this bacteriocin however was not seen.

Numerous lactobacilli identified in this study were found to carry partial pediocin-like operons, often containing the bacteriocin structural gene and associated immunity protein but lacking the appropriate transporters (Table 4b). One potential explanation is that when a strain acquired the gene for pediocin resistance that the neighbouring small bacteriocin structural gene was also transferred, whilst the larger transporters were not.

Although not included in the *Lactobacillaceae* family, several *Carnobacterium* strains were included in the preceding genomic study (Sun et al., 2015). Numerous bacteriocins have been attributed to this genus previously (Quadri et al., 1994, Tulini et al., 2014). While the source of antimicrobial activity from *C. maltaromaticum* DSM20342 is unclear, *C. maltaromaticum* DSM 20722 was found to produce the class IIa bacteriocin cbnB2 and cbnBM1, the class IIc bacteriocin cbnX was also produced by the strain (Tulini et al., 2014). CbnB2 contains an N2Y mutation which was also previously seen by Tulini *et al.* (Tulini et al., 2014).

Class IIb

The class IIb bacteriocins are comprised of unmodified two peptide bacteriocins, whose activity is dependent on the synergistic activity of both peptides which interact to form a single antimicrobial unit (Nissen-Meyer et al., 2010). These bacteriocins are likely to act by forming membrane spanning pores which result in the leakage of small molecules from the cell. Such bacteriocins tend to contain conserved GxxxG or AxxxA motifs which are responsible for close helix interactions between each bacteriocin peptide (Nissen-Meyer et al., 2010). A wide range of class IIb bacteriocins were identified by BAGEL in this study (Table 5).

L. murinus DSM 20452 was one of the strains which demonstrated bacteriocin production. MALDI TOF MS identified masses which correlate with a two-peptide bacteriocin identified by BAGEL

(muricidin). Both peptides of muricidin display homology to the class IIa bacteriocin plantaricin S, with the α peptide displaying 41% amino acid identity to pln S α and the β peptide 48% to pln S β . The β peptide found here however lacks the AxxxA motif found in pln S β , a sequence which has been shown to be important for helix-helix interactions in pln S (Soliman et al., 2011).

Another two-peptide bacteriocin (acidocin X) was also identified from *L. acidophilus* DSM 20079. Correlation between the bacteriocins identified by BAGEL and MALDI TOF MS results led to the identification of two, bacteriocin like, peptides. The first of these was a 35 amino acid peptide displaying 53% identity with the enterocin X β peptide. The second peptide was not identified in BAGEL and was found by manual analysis of the bacteriocin operon, this displays 25% identity to the enterocin X α peptide.

Class IIc

Class IIc bacteriocins are also known as circular bacteriocins due to the covalent linkage of the N- and C-termini. The compact circular structure of these bacteriocins can contribute to their temperature and pH stability (Gabrielsen et al., 2014). These circular bacteriocins permeabilize the target cell membrane, resulting in a loss of membrane potential which leads to cell death (Van Belkum et al., 2011). Despite having similar modes of action, this class of bacteriocins are further broken down into two subgroups, based on the isoelectric point of the peptides and the conservation seen amongst the groups (Acedo et al., 2015). Currently, there are two examples of class IIc bacteriocins produced from lactobacilli, both of which belong to subgroup II. Originally identified as two separate class IIc bacteriocins, Gassericin A (*L. gasseri* LA39) and reuterin 6 (*L. reuteri* LA6) have now been shown to be identical (Kawai et al., 2001, Arakawa et al., 2010). Acidocin B (*L. acidophilus* M46), originally thought to be linear, has also been recently reclassified as a circular bacteriocin. *Leuconostoc mesenteroides* TK41401 has also been shown to produce leucocyclicin Q, a subgroup I circular bacteriocin.

From the analysis carried out in this study, *L. paracasei* subsp. *paracasei* DSM 5622 was found to produce a potential class IIc bacteriocin (paracyclicin), with a structural gene displaying 64% amino acid identity to butyrivibriocin AR10 (Kalmokoff et al., 2003). The operon contains a putative ABC permease, ATPase and a protein belonging to the DUF 95 protein family, all of which have been associated with the gene clusters of circular bacteriocins (Gabrielsen et al., 2014). Upon purification of the bacterial supernatant, a mass of 5905.75 Da was identified as the causative agent of antimicrobial activity. This mass correlates closely with the predicted mass of the mature bacteriocin structural peptide which is calculated as 5906.87 Da. It is clear that paracyclicin belongs to the subgroup II circular bacteriocins, due to a high level of conservation found within the group (Table 6). Despite this conservation, this novel bacteriocin does display variation in certain conserved regions which is not seen in the rest of the class. *L. nodensis* DSM 19682 was also found to encode one such potential bacteriocin, however, no antimicrobial activity was observed with this strain.

Class IId

Class IId bacteriocins are single peptide, linear bacteriocins which do not display homology to the pediocin like bacteriocins (Cotter et al., 2013). This class of bacteriocins displays a high degree of diversity and numerous class IId bacteriocins have been characterised from lactobacilli previously (Table 1). *In silico* analysis of the *Lactobacillus* dataset identified numerous novel structural genes (Table 7) with several shown to be produced.

L. paralimentarius DSM 13961 was one such strain displaying the production of a class IId bacteriocin (paralimenterocin). The paralimenterocin structural gene identified encodes a 44 amino acid single peptide bacteriocin whose closest homolog appears to be the relatively uncharacterised bacteriocin BacSJ2-8 to which it has 77% identity (Kojic et al., 2010). The mode of action of both of these bacteriocins remains unclear.

L. equicursoris DSM 19284 is also highly likely to produce a novel class IId bacteriocin (equicursorin). The strain displayed antimicrobial production upon analysis, but MALDI TOF MS did

not identify an associated mass. *In silico* BAGEL analysis identified three putative bacteriocin operons, two of which encoded larger bacteriolysins of approximately 30kDa, the remaining operon encodes a homolog of lactococcin 972. SDS PAGE analysis of the concentrated culture supernatant identified a mass between the 5kDa and 10kDa markers which displayed antimicrobial activity once overlaid with *L. delbrueckii* subsp. *bulgaricus* LMG 6901 (Supplementary Figure 2). This mass correlates well with the predicted mass (approximately 7kDa) of the lactococcin 972 homolog 'equicursorin'. Lactococcin 972 is unique with respect to its activity in comparison to other class II bacteriocins. These bacteriocins do not induce pore formation in the cells but instead act by binding to lipid II and inhibiting septum formation. Lactococcin 972 is also unusual in that its biologically active form is as a homodimer (Martinez et al., 2000, Martinez et al., 2008). Given that only two such bacteriocins have been identified, it was surprising that four further lactococcin 972-like operons were identified in genomic dataset screened in this study (Table 7 (b)). An *in silico* screen carried out by Letzel *et al.* (Letzel et al., 2014) identified 9 further Lactococcin 972 operons in anaerobic bacteria, thus due to the expansion of this group, these bacteriocins may warrant a separate classification, given their unique mode of action when compared to other class II bacteriocins.

Bacteriolysins (Formerly Class III Bacteriocins)

In the *Lactobacillus* dataset, a number of homologs of the bacteriolysin helveticin (Joerger and Klaenhammer, 1986) were found to be encoded, with several displaying *in vitro* antimicrobial activity. The approximate size of these proteins was determined using SDS PAGE overlay assays, as MALDI TOF MS wasn't used to determine the size of these larger proteins. Several strains encoded numerous helveticin homologs, however, SDS PAGE overlays were not able to identify which of these homologs was actually produced as all had masses of approximately 37 kDa (Supplementary Figure 3).

L. intestinalis DSM 6629 was shown to produce one of these helveticin homologs, with four potential structural genes found within the genome ranging from 38% to 67% amino acid identity to

helveticin J. *L. kitasatonis* DSM 16761 also produced a helveticin like peptide, the strain encodes two such proteins displaying 35% and 41% identity to helveticin J. Two *L. amylovorus* strains (DSM 16698 and DSM 20531) were shown to produce a helveticin homolog. *L. amylovorus* DSM 16698 encodes four of such proteins, whilst *L. amylovorus* DSM 20531 encodes three. Both share a single identical helveticin homolog but it is unclear whether this is the protein produced by both strains. *L. kalixensis* DSM 16043 also produces a helveticin-like protein, with 3 homologs encoded within the genome displaying, 34%, 49% and 50% amino acid identity to helveticin J.

BAGEL also identified a helveticin homolog (77% identity to helveticin J) from *L. crispatus* DSM20584. Interestingly, analysis of the results of a previous exoproteomic study identified the secretion of this protein (Johnson et al., 2016). The antimicrobial activity of the strain in this study was determined to be due to a small peptide by an SDS PAGE overlay assay, this is most likely a lactacin F homolog (Fremaux et al., 1993) or else a novel TOMM like peptide.

Discussion

This study gives the first complete assessment of bacteriocin production across the *Lactobacillus* Genus Complex, combining both *in silico* and laboratory based screening methods. This combination of approaches allows for a more representative estimation of bacteriocin production to be calculated. Well-diffusion assays and MALDI TOF MS allows for the confirmation of *in vitro* bacteriocin production by cells. Bacteriocin production however can be a highly regulated process, with strains requiring specific conditions and environments to induce production of these antimicrobials (Diep et al., 2000, Maldonado-Barragan et al., 2013). Such regulations would make it extremely difficult to identify the bacteriocins found here using *in silico* screens if we were to rely on *in vitro* screening methods alone. Thus, the use of BAGEL and BLAST bacteriocin screens allows us to identify these bacteriocin operons from the *Lactobacillus* Genus Complex without the shortcomings and restrictions of laboratory based screens.

In silico analysis has allowed us to determine the overall bacteriocinogenic potential of the *Lactobacillus* genus. Of the 213 strains analysed, 51 were identified by BAGEL or in BLAST screens as harbouring what appears to be a complete bacteriocin or helveticin like operon, a prevalence of 23.94%. If we focus on the lactobacilli, of the 175 strains analysed only 25 were found to encode bacteriocin operons (14%). If helveticin operons and those of previously characterised bacteriocins are included, of the *Lactobacillus* species analysed 30% were found to encode at least one antimicrobial. This figure of 30% is surprisingly high given that lactobacilli are not associated with the production of more traditional antibiotics formed by non-ribosomal peptide synthetases (NRPS) and polyketide synthases (PKS). Given the extent of bacteriocin production within the genus, the production of antimicrobials by these means may be unnecessary, especially given the size of such NRPS and PKS operons and the subsequent energy it would take for their production. Thus, bacteriocin production may supplant the need for NRPS and PKS enzyme complexes in certain genera.

There was a high degree of novelty within the bacteriocins identified by BAGEL in this study. Of all the structural genes identified here, 73% had not previously been characterised. Screening of these strains identified five novel functional bacteriocins (muricidin, acidocin X, paracyclicin, paralimenterocin and equicursorin) from a range of bacteriocin classes. In addition, five novel producers of helveticin-like peptides were also identified. The abundance of homologs of helveticin-like bacteriolysins encoded by lactobacilli is surprising given how little these proteins have been characterised to date. The observation that most strains in the *L. acidophilus* group encode helveticin homologs with significant homology suggests that this trait was derived from a common ancestor and then disseminated by horizontal transfer. Apart from narrow spectrum antimicrobial activity, no other function has been ascribed to these proteins. The role these proteins play in the life cycle of this narrow branch of strains warrants further study.

The variety and distribution of bacteriocins throughout the genus is interesting when compared to the results of other *in silico* screens which were carried out. Letzel *et al.* (Letzel et al., 2014) used BAGEL and other tools to screen the genomes of 211 anaerobes for bacteriocin encoding genes (no lactobacilli were included in the screen, and helveticin like proteins were excluded). Of these 211 strains, just over 25% were found to encode a bacteriocin like peptide. Thus despite the differences in the make-up of the datasets, there is a similar level of bacteriocin encoding genes found in both groups. While the overall levels may be similar, the diversity of the bacteriocins encoded differs greatly. Of the bacteriocins encoded in the anaerobic dataset, 78% were found to be class I modified bacteriocins, while in the *Lactobacillus* Genus Complex this value is only 17%. One similarity between these sets of results, however, is the presence of lactococcin 972 like bacteriocins. 9 novel homologs were identified in the anaerobic bacteria, this result taken with the number of novel homologs identified from the lactobacilli suggests that this group of unique bacteriocins merit their own class of bacteriocins in the future given their unique mode of action and increasing prevalence.

In a bioinformatics screen of *Bacillus* species for bacteriocin operons (Zhao and Kuipers, 2016), the overall level of bacteriocins encoded by such strains was much higher, with 583 putative bacteriocin operons encoded in the genomes of 328 strains. 89% of these strains, covering 50 different species encode a bacteriocin, a much higher level than seen in the anaerobic bacteria and the lactobacilli. The diversity of encoded bacteriocins again differs to that of the lactobacilli with 66% of operons identified here encoding class I bacteriocins. This difference suggests that there is not an even distribution in the types of bacteriocins across genera, with the lactobacilli in particular relying on the production of class II bacteriocins in comparison to other groups. A similar high prevalence of bacteriocin operons can be found in the cyanobacteria, with 145 putative bacteriocin gene clusters being identified in 43 of the 58 complete and partial genomes screened (Wang et al., 2011). It must be remembered, however, that in both studies these operons were not manually analysed so, in reality, overall levels may be lower.

The inter-species diversity of bacteriocin production can be seen in a screen carried out, whereby the genomes of 169 *Streptococcus mutans* strains were screened by BAGEL for bacteriocin operons (Liu et al., 2016). 211 bacteriocin operons were found distributed amongst 157 strains, of which 32 were lantibiotic operons. These results show that despite carrying out a comprehensive analysis of bacteriocin production in lactobacilli, a high level of diversity within each species can still result in novel bacteriocins being identified.

The environment from which strains are isolated may also influence their bacteriocinogenic potential. 37.5% of strains isolated from human and animal microbiomes encoded bacteriocins or bacteriolysins, this is over twice the value for strains isolated from food, wine and beer, plants and the environment at 16.67%. The microbiota of animals is a complex environment with microbes under constant competition for nutrients and resources (Kostic et al., 2013). Bacteriocin production can provide a competitive advantage for strains, allowing them inhibit sensitive strains thus reducing competition and allowing them to establish themselves in a complex community (Dobson et al.,

2012, Walsh et al., 2008, Gillor et al., 2009). This may suggest why a greater proportion of lactobacilli from these environments encode bacteriocins. Environments such as fermented foods would provide a much narrower niche for the growth of microbes. Less competition here may negate the need for these bacteria to expend energy on bacteriocin production.

Given the association of lactobacilli with probiotics and food production, the knowledge of their potential to produce antimicrobials is of great value (Sanders and Klaenhammer, 2001). Bacteriocin production may increase their ability to establish themselves in a community such as the gut, or provide a natural mechanism to inhibit the growth of food spoilage microorganisms (Walsh et al., 2008, Yang et al., 2014). Thus bacteriocin production can prove a useful trait for an industrially important group of bacteria. Previously, the isolation of bacteriocins from lactobacilli relied on intensive laboratory screens of individual cultures. The use of tools such as BAGEL and BLAST however now allow for the rapid identification of bacteriocin operons within strains, and with the increasing availability of genomic data, these tools are becoming more relevant.

Materials and Methods

Bacteriocin Identification

The bacteriocin mining tool BAGEL2 was used to identify putative bacteriocin operons (de Jong et al., 2010) and the genome visualisation tool ARTEMIS was subsequently used for manual analysis of the bacterial genomes (Rutherford et al., 2000). To determine the degree of novelty in the bacteriocins identified by BAGEL2, BLASTP searches were done for each putative bacteriocin peptide against those identified in the BAGEL screen. The levels of identity described in this study are derived from Clustal Omega. For bacteriocin analysis using specific “driver” sequences, the BLASTP program was used using default parameters. The driver sequences used were NisC (GenBank Accession no. CAA79470.1), LtnM1 (GenBank Accession no. NP_047321.1), VenL (GenBank Accession no. AEA03262.1), TrnC and TrnD from *Bacillus thuringiensis* DPC 6431.

Bacterial Strains

The bacterial strains screened for bacteriocin production and the conditions for growth are listed in Supplementary Table 2. Anaerocult A gas packs (Merck, Darmstadt, Germany) were used to generate anaerobic conditions.

Bacteriocin Assays

Bacteriocin activity was analysed via well diffusion assays against the indicator organisms listed in Supplementary Table 3. Briefly, each strain screened was grown in broth under the appropriate conditions. The cell free supernatant of each culture was prepared by centrifuging the fully grown culture at 4000 RCF for 20 minutes, the pH was adjusted to pH7 using sodium hydroxide to negate any antimicrobial activity which may be caused by the acidity of the cell free supernatants. Fifty microlitres of an overnight culture of each indicator was then added to 20 ml of the appropriate media containing 1.5% agar. Plates were allowed cool and the 7mm wide wells were bored into the

agar. Fifty microliters of the cell free supernatant of the strains being tested was then placed in a well. These indicator plates were refrigerated for two hours prior to incubation.

Mass Spectrometry (MS)

MALDI TOF colony mass spectroscopy was carried out on each of the strains as previously described to identify masses of putative bacteriocins (Field et al., 2010). Here colonies were first mixed with a 70% propan-2-ol 0.1% TFA solution to elute bacteriocin from the cell. Following centrifugation, the subsequent supernatant was spotted on the target pre-coated with CHCA matrix solution. A further layer of matrix solution was then added on top of this supernatant. An Axima TOF²plus MALDI TOF mass spectrometer (Shimadzu Biotech, Manchester, UK) was used to identify the peptide masses using positive-ion reflectron mode.

Sodium Dodecyl Sulfate-Polyacrylamide Gel Electrophoresis (SDS-PAGE)

SDS PAGE was used for the identification of higher molecular weight antimicrobial proteins (bacteriolysins). Cultures were grown overnight in broth and the cell free supernatants were prepared as described above. The proteins from the bacterial supernatant were precipitated by addition of ammonium sulphate salts up to a concentration of 50%. The precipitate was collected by centrifugation and resuspended in water. Supernatants were then incubated with TruPAGE™ LDS sample buffer (Sigma-Aldrich, Wicklow, Ireland) for 10 minutes at 70°C. Samples were run on 12% acrylamide gels at 30 mA, together with Precision Plus Protein™ Dual Xtra prestained protein standards (Bio-Rad, Hertfordshire, UK) which were used to estimate molecular mass with a range of 2-250kDa. The completed gels were divided in two, one half was stained using the EZBlue™ staining reagent (Sigma-Aldrich). The other half was washed with 1% tween-80 (Sigma-Aldrich) for 45 minutes, followed by three 5 minute washes in distilled water. This gel was overlaid with soft MRS agar (0.8% agar), seeded with 0.25% of an overnight culture of *L. delbrueckii* subsp. *bulgaricus* LMG

6901. The plate was incubated overnight to determine the mass of any antimicrobial proteins produced.

Bacteriocin Purification

Carnobacteriocins CbnB2, CbnBM1 and CbnX

Carnobacterium maltaromaticum DSM 20722 was grown overnight in TSA broth, 100 ml of the supernatant was passed through a 5g, 20ml Strata C₁₈-E solid-phase extraction (SPE) column (Phenomenex, Cheshire, UK). The column was washed with 20ml of 30% ethanol and 20ml of 70% 2-propanol (IPA) 0.1% TFA. The 70% IPA eluent was concentrated and applied to a Semi Prep Proteo Jupiter RP-HPLC column (10 x 250mm, 90Å, 4µm) (Phenomenex, Cheshire, UK) running a 20-55% gradient whereby buffer B was 90% acetonitrile. MALDI TOF MS was carried out on fractions to identify the presence of the peptides of interest.

Paracyclisin

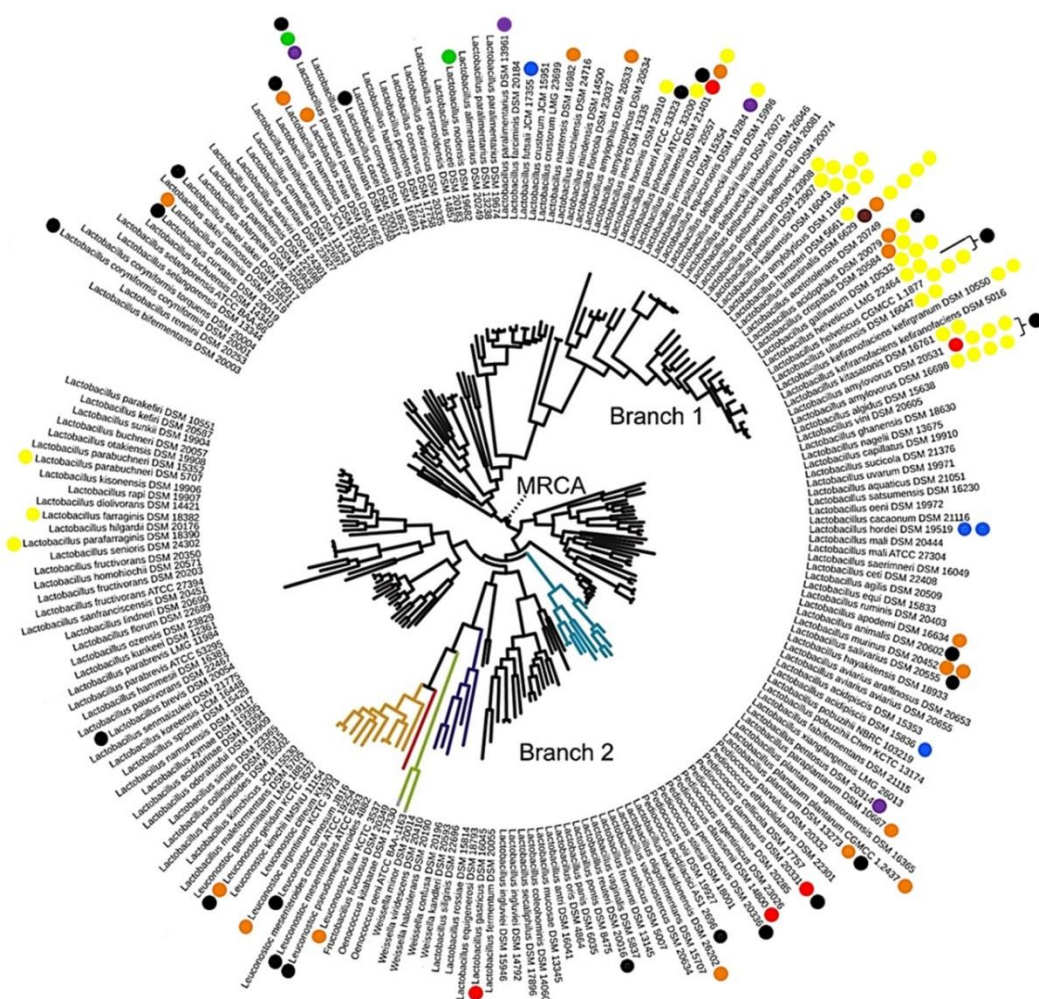
L. paracasei subsp. *paracasei* DSM 5622 was grown overnight in MRS broth. Culture supernatant was passed through a column containing 60g Amberlite XAD beads and washed with 400ml of 50% ethanol and the antimicrobial peptide eluted with 400ml of 70% IPA 0.1% TFA. The IPA was removed and the eluent passed through a 5g, 20ml C₁₈ SPE column pre-equilibrated with methanol and water. The column was washed with 30ml of 50% ethanol and activity eluted with 30 ml of IPA. The IPA was removed from the C₁₈ SPE IPA eluent and the sample applied to a semi preparative Vydac C₄ Mass Spec (10 x 250 mm, 300Å, 5µ) RP-HPLC column (Grace, Columbia, USA) running an acetonitrile and propan-2-ol gradient described as follows: 5-55% buffer B and 0-5% buffer C over 25 minutes followed by and 55-19% buffer B and 5-81% buffer C over 60 minutes, 19-5% buffer B and 81-95% buffer C over 5 minutes where buffer A is Milli Q water containing 0.1% TFA, buffer B is 90% acetonitrile 0.1% TFA and buffer C is 90% propan-2-ol 0.1% TFA. Eluent was monitored at 214nm and fractions were collected at 1 minute intervals. Fractions were assayed

using well diffusion assays against *L. delbrueckii* subsp. *bulgaricus* LMG 6901. MALDI TOF MS was used to determine the mass of the antimicrobial peptide.

Figures and Tables

Figure 1. Distribution of complete bacteriocin operons amongst the *Lactobacillus* Genus Complex

(Adapted from Sun *et al.*)



Legend:	
Species for which a bacteriocin has been previously characterised	●
Class I Bacteriocin	●
Class IIa Bacteriocin	●
Class IIb Bacteriocin	●
Class IIc Bacteriocin	●
Class IId Bacteriocin	●
TOMM	●
Helveticin	●

Table 1. Bacteriocins characterised from species within the *Lactobacillus* Genus Complex

Bacteriocin	Subclass	Producing strain	Origin	Reference
Class I				
Plantaricin W (α and β)	II	<i>Lactobacillus plantarum</i> LMG 2379	Wine	(Holo et al., 2001)
Plantaricin C	II	<i>L. plantarum</i> LL441	Cabrales cheese	(Gonzalez et al., 1994)
Lactocin S ^a	II	<i>L. sakei</i> L45	Sausages	(Mortvedt et al., 1991)
Pediocin PD-1	II	<i>Pediococcus damnosus</i> NCFB1832	Lager Beer	(Green et al., 1997)
Glycocin F	Glycocin	<i>L. plantarum</i> KW30	Fermented corn	(Venugopal et al., 2011)
Class II				
Acidocin A	IIa	<i>L. acidophilus</i> TK9201	Fermented milk (starter)	(Kanatani et al., 1995)
Curvaticin L442	IIa	<i>L. curvatus</i> L442	Greek fermented sausage	(Xiraphi et al., 2006)
Curvaticin 13	IIa	<i>L. curvatus</i> SB13	Sausages	(Sudirman et al., 1993)
Sakacin P (variant) ^b	IIa	<i>L. curvatus</i> LTH1174	Fermented meat	(Cocolin and Rantsiou, 2007)
Plantaricin BM-1	IIa	<i>L. plantarum</i> BM-1	Fermented meat	(Zhang et al., 2013)
Plantaricin C19	IIa	<i>L. plantarum</i> C19	Fermented cucumber	(Atrih et al., 2001)
Plantaricin 423	IIa	<i>L. plantarum</i> 423	Sorghum (beer)	(Van Reenen et al., 2003)
Sakacin P ^c	IIa	<i>L. sakei</i> LTH673	Cured meat	(Tichaczek et al., 1994)
Sakacin A ^d	IIa	<i>L. sakei</i> Lb706	Meat	(Holck et al., 1992)
Sakacin G ^e	IIa	<i>L. sakei</i> 2512	Food origin	(Simon et al., 2002)
Sakacin X ^f	IIa	<i>L. sakei</i> 5	Malt	(Vaughan et al., 2003)
Bavaricin A	IIa	<i>L. sakei</i> MI1401	Sourdough	(Larsen and Norrung, 1993)
Bavaricin MN	IIa	<i>L. sakei</i> MN	Meat (bovine)	(Kaiser and Montville, 1996)
Bacteriocin L-1077	IIa	<i>L. salivarius</i> L-1077	Intestine (broilers)	(Svetoch et al., 2011)
Leucocin A ^{gh}	IIa	<i>Leuconostoc geldium</i> UAL 187	Vacuum-packed meat	(Hastings et al., 1991)
Leucocin C	IIa	<i>Leuc. mesenteroides</i> TA33a	Spoiled vacuum-packed meat	(Papathanasopoulos et al., 1997)
Leucocin 10C ^h	IIa	<i>Leuc. mesenteroides</i> 10	Malted barley	(Vaughan et al., 2001)
Leucocin 683Y	IIa	<i>Leuc. mesenteroides</i> 683	Malted barley	(Vaughan et al., 2001)
Mesentericin Y105	IIa	<i>Leuc. mesenteroides</i> subsp. <i>mesenteroides</i> Y105	Goats milk	(Hechard et al., 1992)
Pediocin PA-1 (ACH) ⁱ	IIa	<i>P. acidilactici</i> PAC1.0	Meat	(Gonzalez and Kunka, 1987)
Pediocin SA-1	IIa	<i>P. acidilactici</i> NRRL B5627	Meat	(Anastasiadou et al., 2008b)
Penocin A	IIa	<i>P. pentosaceus</i> ATCC 25745	Plants	(Diep et al., 2006)
Pediocin SM-1	IIa	<i>P. pentosaceus</i> Mees 1934	Meat	(Anastasiadou et al., 2008a)
Weissellin A	IIa	<i>Weissella paramesenteroides</i> DX	Sausage	(Papagianni and Papamichael, 2011)
Lactobin A ^j	IIb	<i>L. amylovorus</i> LMG P-13139	Corn liquor	(Contreras et al., 1997)
Brevicin 174 (<i>breB</i> and <i>breC</i>)	IIb	<i>L. brevis</i> 174A	Iyokan (fruit)	(Noda et al., 2015)
Lactocin 705 (Lac705 α and Lac705 β)	IIb	<i>L. casei</i> CRL 705	Meat	(Vignolo et al., 1996)
Acidocin LF221 (LF221A and LF221B) ^k	IIb	<i>L. gasseri</i> LF221	Faeces (child)	(Majhenič et al., 2004)
Gasericin T (GatA and GatX)	IIb	<i>L. gasseri</i> SBT2055	Faeces (human)	(Kawai et al., 2000)
Lactacin F (LafA and LafX) ^l	IIb	<i>L. johnsonii</i> VPI11088	Intestine (human)	(Fremaux et al., 1993)
Sakacin T (SakT α and SakT β) ^m	IIb	<i>L. sakei</i> CTC372	Sausages	(Aymerich et al., 2000)
Plantaricin E/F (PlnE and PlnF)	IIb	<i>L. plantarum</i> C11	Fermented cucumber	(Diep et al., 1996)
Plantaricin J/K (PlnJ and PlnK)	IIb	<i>L. plantarum</i> C11	Fermented cucumber	(Diep et al., 1996)
Plantaricin S (Pls α and Pls β) ⁿ	IIb	<i>L. plantarum</i> LPCO10	Green olives	(Stephens et al., 1998)

Table 1. Continued

Bacteriocin	Subclass	Producing strain	Origin	Reference
Plantaricin NC8 (PLNC8 α and PLNC8 β)	IIb	<i>L. plantarum</i> NC8	Ensilage	(Maldonado et al., 2003)
Salivaricin ABP-118 (Abp118 α and Abp118 β)	IIb	<i>L. salivarius</i> UCC118	Intestine (human probiotic)	(Flynn et al., 2002)
Salivaricin CLR 1328 (Sala and Sal β)	IIb	<i>L. salivarius</i> CLR1328	Vagina (human)	(Vera Pingitore et al., 2009)
Salivaricin P (Sln1 and Sln2)	IIb	<i>L. salivarius</i> DPC6005	Intestine (pig)	(Barrett et al., 2007)
Salivaricin T (SalT α and SalT β)	IIb	<i>L. salivarius</i> DPC6488	Intestine (neonate)	(O'Shea et al., 2011)
Acidocin B	IIc	<i>L. acidophilus</i> M46	Food origin	(Leer et al., 1995)
Gassericin A ^o	IIc	<i>L. gasseri</i> LA39	Faeces (child)	(Kawai et al., 1998)
Leucocyclicin Q	IIc	<i>Leuc. mesenteroides</i> TK41401	Japanese pickles	(Masuda et al., 2011)
Acidocin 8912	IId	<i>L. acidophilus</i> TK8912	Dairy origin	(Tahara et al., 1992)
Brevicin 27	IId	<i>L. brevis</i> SB27	Sausages	(Benoit et al., 1997)
Lactocin MXJ 32A	IId	<i>L. coryniformis</i> MXJ 32	Fermented vegetables	(Lu et al., 2014)
Curvalicin BAP2	IId	<i>L. curvatus</i> CWBI-B28	Meat	(Ghalfi et al., 2010)
Curvaticin FS47	IId	<i>L. curvatus</i> FS47	Meat	(Garver and Muriana, 1994)
Sakacin Q (variant) ^p	IId	<i>L. curvatus</i> LTH1174	Fermented meat	(Cocolin and Rantsiou, 2007)
Bacteriocin SJ2-8	IId	<i>L. paracasei</i> BGSJ2-8	Home-made cheese	(Lozo et al., 2007)
Paracin C	IId	<i>L. paracasei</i> CICC 20241	Probiotic	(Pei et al., 2013)
Plantaricin 1.25 α	IId	<i>L. plantarum</i> TMW1.25	Fermented sausages	(Remiger et al., 1999)
Plantaricin 1.25 β	IId	<i>L. plantarum</i> TMW1.25	Fermented sausages	(Remiger et al., 1999)
Plantaricin 149	IId	<i>L. plantarum</i> NRIC 149	Pineapple	(Kato et al., 1994)
Plantaricin 163	IId	<i>L. plantarum</i> 163	Fermented vegetables	(Hu et al., 2013)
Plantaricin A	IId	<i>L. plantarum</i> C11	Fermented cucumber	(Nissen-Meyer et al., 1993)
Plantaricin ASM1	IId	<i>L. plantarum</i> A-1	Corn bread	(Hata et al., 2010)
Plantaricin JLA-9	IId	<i>L. plantarum</i> JLA-9	Suan-Tsai (Chinese fermented cabbage)	(Zhao et al., 2016)
Plantaricin ST31	IId	<i>L. plantarum</i> ST31	Sourdough	(Todorov et al., 1999)
Sakacin Q ^q	IId	<i>L. sakei</i> LTH673	Fermented dry sausage	(Mathiesen et al., 2005)
Salivaricin L	IId	<i>L. salivarius</i> DPC6488	Intestine (neonate)	(O'Shea et al., 2011)
Plantaricin Y	IId	<i>L. plantarum</i> 510	Koshu vineyard	(Chen et al., 2014)
Rhamnosin A	IId	<i>L. rhamnosus</i> 68	Intestinal microbiota (human)	(Dimitrijevic et al., 2009)
Bactofencin A	IId	<i>L. salivarius</i> DPC6502	Intestine (porcine)	(O'Shea et al., 2013)
Bacteriocin LS2	IId	<i>L. salivarius</i> BGHO1	Oral (human)	(Busarcevic and Dalgarrondo, 2012)
Leucocin B	IId	<i>Leuc. mesenteroides</i> TA33a	Spoiled vacuum-packed meat	(Papathanasopoulos et al., 1997)
Mesentericin 52B ^r	IId	<i>Leuc. mesenteroides</i> FR52	Raw Milk	(Revol-Junelles et al., 1996)
Leucocin N	IId	<i>Leuc. pseudomesenteroides</i> QU 15	Nukadoko	(Sawa et al., 2010)
Leucocin Q	IId	<i>Leuc. pseudomesenteroides</i> QU 15	Nukadoko	(Sawa et al., 2010)
Weissellicin 110	IId	<i>Weissella cibaria</i> 110	Plaa-Som	(Sriornual et al., 2007)
Weissellicin L	IId	<i>W. hellenica</i> 4-7	Sian-sianzih	(Leong et al., 2013)
Weissellicin M	IId	<i>W. hellenica</i> QU 13	Pickel barrel	(Masuda et al., 2011)
Weissellicin Y	IId	<i>W. hellenica</i> QU 13	Pickel barrel	(Masuda et al., 2011)
Lactacin B ^s	-	<i>L. acidophilus</i> N2	Food origin	(Barefoot and Klaenhammer, 1983)
Bacteriocin TSU4	-	<i>L. animalis</i> TSU4	Intestine (fish)	(Sahoo et al., 2015)

Table 1. Continued

Bacteriocin	Subclass	Producing strain	Origin	Reference
Curvalicin BAP3	-	<i>L. curvatus</i> CWBI-B28	Meat	(Ghalfi et al., 2010)
Gassericin E	-	<i>L. gasseri</i> EV1461	Healthy vagina (human)	(Maldonado-Barragan et al., 2016)
Plantacin B	-	<i>L. plantarum</i> NCDO1193	Dairy origin	(West and Warner, 1988)
Plantaricin F	-	<i>L. plantarum</i> BF001	Spoiled cat fish filets	(Fricourt et al., 1994)
Plantaricin T	-	<i>L. plantarum</i> LPCO10	Green olives	(Jimenez-Diaz et al., 1993)
Bacteriocin SMXD51	-	<i>L. salivarius</i> SMXD51	Faeces (chicken)	(Messaoudi et al., 2012)
Salivaricin B	-	<i>L. salivarius</i> M7	Food origin	(Ten Brink et al., 1994)
Bacteriolysin				
Helveticin J		<i>L. helveticus</i> NCDO481	Dairy origin	(Joerger and Klaenhammer, 1986)

Characterised bacteriocins with identicle amino acid sequences: ^aSakacina M/lactocin S from *L. sakei* 148 (Sobrinho et al., 1992, Skaugen et al., 1997). ^bVarient of sakacin P from *L. curvatus* L442 (Cocolin and Rantsiou, 2007). ^cSakacin 674 from *L. sakei* 674 (Holck et al., 1994). ^dCurvacin A from *L. curvatus* LTH1174 (Tichaczek et al., 1993) and sakacin K from *L. sakei* CTC 494 (Hugas et al., 1995). ^eBacteriocin R1333 from *Lb. sakei* R1333 (Todorov et al., 2011). ^fSakacin X from *L. curvatus* 2711 (Hequet et al., 2007) and *L. curvatus* CRL705 (Hebert et al., 2012). ^gLeucocin A-TA33a from *Leuonostoc mesenteroides* TA33a (Papathanasopoulos et al., 1997) and Leucocin B-Ta11a from *Leuc. carnosum* Ta11a (Felix et al., 1994). ^hLeucocin A-4010 and Lecucocin B-4010 from *Leuc. carnosum* 4010 (Budde et al., 2003). ⁱAlso produced by *L. plantarum* WHE92 (Ennahar et al., 1996). ^jAmilovorin L471 from *L. amylovorus* DCE471 (De Vuyst et al., 2004). ^kGassericin K7 (K7A y K7B) from *L. gasseri* K7 (Pernel et al., 2010). ^lLactacin F from *L. acidophilus* 30SC (Oh et al., 2011). ^mSakacin T (SakT α and SakT β) from *L. sakei* 5 (Vaughan et al., 2003), *L. curvatus* 2711 (Hequet et al., 2007) and *L. curvatus* CRL705 (Hebert et al., 2012). ⁿAlso produced by *L. pentosus* B96 (Hurtado et al., 2011). ^pReuterin 6 from *L. reuteri* LA6 (Kawai et al., 2001). ^oVarient of sakacin Q from *L. curvatus* L442 (Cocolin and Rantsiou, 2007) and *L. curvatus* CRL705 (Hebert et al., 2012). ^qSakacin Q from *L. sakei* Lb674 (Mathiesen et al., 2005) and sakacin Q from *L. curvatus* CRL705 (Hebert et al., 2012). ^rMesentericin B105 from *Leuc. mesenteroides* subsp. *mesenteroides* Y105 (Hécharde et al., 1999). ^sAcidocin J1132 from *L. acidophilus* JCM1132 (Tahara et al., 1996). The - symbol represents bacteriocins which were difficult to accurately classify based on information retrieved.

Table 2. Spectrum of inhibition of bacteriocin producing strains against a range of indicator strains

Bacteriocin Producers	Strain (DSM)	Activity of Bacteriocin Producers vs. Indicator Organisms*								
		<i>L. delbrueckii</i> subsp. <i>bulgaricus</i>	<i>L. delbrueckii</i> subsp. <i>lactis</i>	<i>L. amylovorus</i>	<i>L. casei</i>	<i>L. plantarum</i>	<i>L. rhamnosus</i>	<i>Listeria innocua</i>	<i>Enterococcus saccharolyticus</i>	<i>E. mundtii</i>
<i>L. paralimentarius</i>	13961				++	+++	++		+	+++
<i>L. murinus</i>	20452	+								
<i>L. hordei</i>	19519	++	++			++		+++	+++	+++
<i>L. intestinalis</i>	6629	+++		+						
<i>L. paracasei</i> subsp. <i>paracasei</i>	5622	+	+							
<i>L. acidophilus</i>	20079	++	++	+					+	
<i>L. agilis</i>	20509							+		
<i>L. crispatus</i>	20584	++	+	+						
<i>L. equicursoris</i>	19284	++								
<i>L. pentosus</i>	20314	+								
<i>L. kalixensis</i>	16043	+								
<i>L. amylovorus</i>	20531	+								
<i>L. kitasatonis</i>	16761	++								
<i>P. damnosus</i>	20331	+++								
<i>C. maltaromaticum</i>	20342	+	+							
<i>C. maltaromaticum</i>	20722	++	+					+	++	

Activity of pH neutralised cell free supernatants from bacteriocin producers in agar well diffusion assay. Inhibition of indicators is described in radius (mm) of the zone of inhibition in WDA, scores are as follows: + = 0.5 – 2mm, ++ = 2.5 – 5mm, +++ = >5mm

Table 3. Potential Lantibiotic/Lantipeptide Structural Peptides

Species	Strain	Potential Unmodified Lantibiotic/Lantipeptide Sequence
<i>L. taiwanensis</i>	DSM 21401	TSTGCCNGPSKLQG
<i>L. amylovorus</i>	DSM 20531	AKSYSAYSSCSCVNPPCPIATMD
<i>L. gastricus</i>	DSM 16045	GTETAQSTPAISRVTLIARKSSAKCISWISFSAGGLNSYKSKC
<i>P. damnosus</i> (Pediocin PD-1)	DSM 20331	KKIKKSSSGDICTLTSECDHLATWVCC

Table 4 (a). Structural Genes for Complete Class IIa Operons

Species	Strain	Structural Peptide	Homolog (%Amino Acid Identity)
<i>L. hordei</i>	DSM 19519	KYYGNGVTCGKHSCSVDWGKATTCIINNGAMAWATGGHQGTHKC	Coagulin (100%)
		KYYGNGVSCCKKHGCKVNWGQAFTCSVNRNFANFGHGNC	Plantaricin 423 (74%)
<i>L. acidipiscis</i>	DSM 15836	KYYGNGLHIPKHGKPYINWGQAIQSIGKISYHGWVNGITSGAAGVGRH	Hiracin JM79 (44%)
<i>L. futsaii</i>	JCM 17355	KYYGNGVSCGKHTCKVNWGQAWNESVNRWGNWVNGLTGLRQH	Plantaricin 423 (57%)
<i>C. maltaromaticum</i>	DSM 20722	AISYGNGVVCNKEKCWVNKAENKQAITGIVIGGWASSLAGMGH	Carnobacteriocin cbn BM1 (100%)
		VYYGNGVSCSKTKCSVNWGQAFQERYTAGINSFVSGVASGAGSIGRRP	Carnobacteriocin cbn B2 (98%)

(b) Structural Genes for Incomplete Class IIa Operons

Species	Strain	Structural Peptide	Homolog (%Amino Acid Identity)
<i>L. agilis</i>	DSM 20509	SRYYGNGITCGKHKCTVNWGQAWTCGVNRLANFGHGNC	Plantaricin 423 (73%)
<i>L. aquaticus</i>	DSM 21051	KNYGNGVYCTKKHGYKVDWGQAWSIIGNNSAANSTTRGAAGWWSK	Avicin A (74%)
<i>L. rennini</i>	DSM 20253	KYYGNGVSCSKHSCSVDWGKALTCTINNGAMAWTTGGHQGNHHC	Pediocin Ach/PA-1 (89%)
<i>L. ruminis</i>	DSM 20403	KYYGNGVYCGKHKCRVDWGQAWGCSVNRWGAAVGTGGKATIGHC	Pediocin Ach/PA-1 (55%)
<i>P. pentosaceus</i>	DSM 20336	KYYGNGLYCGKHSCSVDWGKATTCIINNGAMAWATGGHQGTHKC	Pediocin Ach/PA-1 (93%)
<i>C. maltaromaticum</i>	DSM 20342	AISYGNGVVCNKEKCWVNKAENKQAITGIVIGGWASSLAGMGH	Carnobacteriocin cbn BM1 (100%)

Table 5. Potential Class IIb Structural Genes

Species	Strain	Structural Peptide	Produced <i>in vitro</i>	
<i>L. murinus</i>	DSM 20452	YNRLAGQIGHYTGKAVIVGATVVGIALSLF	Produced <i>in vitro</i>	(Muricidin)
		KRGLGYHIVDAVVSFGKGFDAF		
		YDIEKALWGGYGYQLGWRNKWNLSHRYFKI		
		GVPGWYYGMLWKIGVSGYKHKRDIMNGFDRGFNNYPK		
<i>L. acidophilus</i>	DSM 20079	SNNIFWTRVGVGWAAEARCMIKPSLGNWTTKAVSCGAKGLYAAVRG	Produced <i>in vitro</i>	(Acidocin X)
		VAPIVYPIAGYVMKQMFHSDQIIKGFKRGWKKYK		
<i>L. taiwanensis</i>	DSM 21401	NRWGDVLSAASGAGTGKACKSFGPWGMAICGSNRRLFWLYS		
		RNNWQTNVGGAVGSAMIGATVGGTICGPACAVAGAHYLPILWTGVTAATGGFGKIRK		
<i>L. crispatus</i>	DSM 20584	NRWTNAYSAAALGCAVPGVKYKKLGGVWGAVIGGVGGAAVCGLAGYVRKG		
		SKGKGRRNNWAGNTIGIVSSAATGAALGSAICGPGCGFVGAWHGAVGWTAVASFSGAFGKIRK		
<i>L. nantensis</i>	DSM 16982	SFKGFVQGFINGLTGKKH		
		KGPWNYKTGYNLGKWISKRF		
<i>L. apodemi</i>	DSM 16634	YDIEKALWKGYGYQLGWRNWKWNLSHRYFKI		
		GVPGWYYSMWLWKIGVSGYKHKRDIMSGFDKGFNNYPK		
<i>L. plantarum</i>	DSM 13273	RRSRKNGIGYAIGYAFGAVERAVLGGSRDYNK		
		GAWKNFWSLRKGFYDGEAGRAIR		
		FNRGGYNFGKSVRHVVDAIGSVAGIRGILKSIR		
		VFHAYSARGVRNNYKSAVGPAWVISAVRGFIHG		
<i>L. plantarum</i> subsp. <i>plantarum</i>	CGMCC 1.2437	RRSRKNGIGYAIGYAFGAVERAVLGGSRDYNK		
		GAWKNFWSLRKGFYDGEAGRAIR		
		FNRGGYNFGKSVRHVVDAIGSVAGIRGILKSIR		
		VFHAYSARGVRNNYKSAVGPAWVISAVRGFIHG		
<i>L. paraplantarum</i>	DSM 10667	FNRGGYNFGKSVRHVVDAIGSVAGIRGILKSIR		
		VFHAYSARGVRNNYKSAVGPAWVISAVRGFIHG		
<i>L. intestinalis</i>	DSM 6629	RHSVPYSYGYQSGRGFKGAAAAYNIIKTVASFFE		
		KRKKHHPWYWSIQEFGRGFLAGLASKYNL		
<i>L. rhamnosus</i>	DSM 20021	IGPLAIPVAAILGFLATDAWHADELVAGVKQGWERS		
		DNGNLWTFIGKAIGSTARSWAEGAMFAPAIGPAKEIVDKLNGN		
<i>L. zeae</i>	DSM 20178	NAWGNVANGALNGAATGARFGKNLGPWGMIGGMALGAGIGGYFGYNG		
		RNTWQQNVSGVAGAAAGGAALGAVVGGPAGAFGLAHYGPILWTAVTGFTGGF		
<i>Leuc. fallax</i>	KCTC 3537	CPLPIVVTVAAASGAHFVAKDGWNHLDQIRSGWRKSGNSKW		
		STDGSWEDFGAGLHKTNTVIYAGTTVARAHTRSHQRCFTGNKW		

Table 6. Alignment of Class IIc Subgroup II Bacteriocins

Bacteriocin	Structural Peptide
Gassericin A	IYWIADQFGIHLATGTARKLLDAMASGASLGTAFAAILGVTLPAWALAAAGALGATAA
Acidocin B	IYWIADQFGIHLATGTARKLLDAVASGASLGTAFAAILGVTLPAWALAAAGALGATAA
Butyrivibriocin AR10	IYFIADKMGIQ LAPAWYQDIVNWVSAGGTLT TGFAI IGVTVPAWIAEAAAAFGIASA
<i>L. paracesei</i> subsp. <i>paracesei</i> DSM 5622 (Paracyclicin)	IYFIANKLGIHLAPGWYQDMVNYVSAGGSLAGAFSVVAGVTLP AWIVPIATAFGAVSA
<i>L. nodensis</i> DSM 19682	-IWIAGLFGIHLDNSLESKLVSGILNGGSAAGVFAAMLGITLP AWAAAAATAMGATAA
	:** :**:* . .::: : *. : *: : **:*** * *: * .:*

* = Positions with a single conserved residue

: = Conservation between groups with strongly similar properties, scoring > 0.5 in the Gonnet PAM
250 matrix

. = Conservation between groups with weakly similar properties, scoring ≤ 0.5 in the Gonnet PAM
250 matrix

Table 7. Potential Class IId Structural proteins

Species	Strain	Structural Protein
<i>L. paralimentarius</i>	DSM 13961	NFFGGSNGYSWRDKKGHWHTVTSVSTVAQIIGNGWGSAGAPGVGQR
<i>L. pentosus</i>	DSM 20314	KSNTYSLQMGSVVRTATKIFKKMEW
<i>L. hokkaidonensis</i>	DSM 26202	VTLSVATHSKNGLKKFFKWVRKL
<i>L. xiangfangensis</i>	LMG 26013	KLVKLYTAEPYTFYRDTRTKKIVMRQTTGYSAPHLQHVADGWVRSAPHL
<i>L. paracasei</i>	DSM 5622	DSIRDVSPTFNKIRRWFDGLFK
<i>L. murinus</i>	DSM 20452	YDIEKALWGGYGYQLGWRNKWNLSHRYFKI
<i>Leuc. kimchii</i>	IMSNU 11154	KSFWSWASDASSWLSGPQQPNSPLLKKKR
<i>Leuc. geldium</i>	KCTC 3527	KRVYIPNGNGAWLDSNTGKGGVDWNVAVPALGSIMVNGWAQNGPLAHLHP
(b) Potential Class IId Lactococcin 972 Homologs		
Species	Strain	Structural Protein
<i>L. equicursoris</i> (equicursorin)	DSM 19284	GGTWNYGVGSKYVWSYYSHNSKTHKASVEGKYVTSVSGWIKETQARASAAKAAAGNQSYDDVK
<i>L. amylophilus</i>	DSM 20533	GGTWNYGVGLTGTGFGYSDYLNHNSKTHSASVGRKSDCNKVTCTKGVWAQSKYTKIPPTGLNYWWSVS
<i>L. graminis</i>	DSM 20719	GGTWYSGFSGTKVYSQYYHGSKKHSATAKNGWGAGVRNTQKAGIWAYSSVNSTLTGNKTYWAVY
<i>L. hamsteri</i>	DSM 5661	GGVWNYGVGKKYVWSYYSHHRLTHKSSVEGKYSSSGWVSPGTEARASAEKAQHGNKSYFDVE
<i>Leuc. argentinum</i>	KCTC 3773	GGDWRHGVGSYYVWSYFHNRYRNHSSSVSGQYFASSGRTSPGYDAQASAPKSLFGNKAYYDFW

Supplementary Table 1. Source of Strains

Species Name	StrainID	Source	Antimicrobial Encoded
<i>Lactobacillus agilis</i>	DSM-20509	Environment	
<i>Lactobacillus aquaticus</i>	DSM-21051	Environment	
<i>Lactobacillus concavus</i>	DSM-17758	Environment	
<i>Lactobacillus coryniformis torquens</i>	DSM-20004	Environment	
<i>Lactobacillus paracollinoides</i>	DSM-15502	Environment	
<i>Lactobacillus sharpeae</i>	DSM-20505	Environment	
<i>Weissella kandleri</i>	DSM-20593	Environment	
<i>Carnobacterium divergens</i>	DSM-20623	Food	
<i>Carnobacterium maltaromaticum</i>	DSM-20342	Food	
<i>Carnobacterium maltaromaticum</i>	DSM-20722	Food	Yes
<i>Lactobacillus acetotolerans</i>	DSM-20749	Food	
<i>Lactobacillus acidifarinae</i>	DSM-19394	Food	
<i>Lactobacillus acidipiscis</i>	DSM-15836	Food	Yes
<i>Lactobacillus acidipiscis</i>	DSM-15353	Food	
<i>Lactobacillus algidus</i>	DSM-15638	Food	
<i>Lactobacillus alimentarius</i>	DSM-20249	Food	
<i>Lactobacillus bif fermentans</i>	DSM-20003	Food	
<i>Lactobacillus capillatus</i>	DSM-19910	Food	
<i>Lactobacillus casei</i>	DSM-20011	Food	
<i>Lactobacillus collinoides</i>	DSM-20515	Food	
<i>Lactobacillus crustorum</i>	LMG-23699	Food	
<i>Lactobacillus crustorum</i>	JCM-15951	Food	
<i>Lactobacillus curvatus</i>	DSM-20019	Food	
<i>Lactobacillus delbrueckii bulgaricus</i>	DSM-20081	Food	
<i>Lactobacillus delbrueckii delbrueckii</i>	DSM-20074	Food	
<i>Lactobacillus delbrueckii indicus</i>	DSM-15996	Food	
<i>Lactobacillus delbrueckii lactis</i>	DSM-20072	Food	
<i>Lactobacillus farciminis</i>	DSM-20184	Food	
<i>Lactobacillus frumenti</i>	DSM-13145	Food	
<i>Lactobacillus fuchuensis</i>	DSM-14340	Food	
<i>Lactobacillus futsaii</i>	JCM-17355	Food	Yes
<i>Lactobacillus hammesii</i>	DSM-16381	Food	
<i>Lactobacillus harbinensis</i>	DSM-16991	Food	
<i>Lactobacillus helveticus</i>	CGMCC-1.1877	Food	Yes
<i>Lactobacillus kefiranofaciens kefiranofaciens</i>	DSM-5016	Food	
<i>Lactobacillus kefiranofaciens kefirgranum</i>	DSM-10550	Food	Yes
<i>Lactobacillus kefiri</i>	DSM-20587	Food	
<i>Lactobacillus kimchicus</i>	JCM-15530	Food	
<i>Lactobacillus kimchiensis</i>	DSM-24716	Food	
<i>Lactobacillus kisonensis</i>	DSM-19906	Food	
<i>Lactobacillus koreensis</i>	JCM-16448	Food	
<i>Lactobacillus mindensis</i>	DSM-14500	Food	

Supplementary Table 1. Continued

<i>Lactobacillus namurensis</i>	DSM-19117	Food	
<i>Lactobacillus nantensis</i>	DSM-16982	Food	Yes
<i>Lactobacillus nodensis</i>	DSM-19682	Food	Yes
<i>Lactobacillus odoratitofui</i>	DSM-19909	Food	
<i>Lactobacillus otakiensis</i>	DSM-19908	Food	
<i>Lactobacillus panis</i>	DSM-6035	Food	
<i>Lactobacillus parabrevis</i>	LMG-11984	Food	
<i>Lactobacillus parabrevis</i>	ATCC-53295	Food	
<i>Lactobacillus paracasei tolerans</i>	DSM-20258	Food	
<i>Lactobacillus parakefiri</i>	DSM-10551	Food	
<i>Lactobacillus paralimentarius</i>	DSM-13238	Food	
<i>Lactobacillus paralimentarius</i>	DSM-13961	Food	Yes
<i>Lactobacillus perolens</i>	DSM-12744	Food	
<i>Lactobacillus plantarum plantarum</i>	CGMCC-1.2437	Food	Yes
<i>Lactobacillus pontis</i>	DSM-8475	Food	
<i>Lactobacillus rapi</i>	DSM-19907	Food	
<i>Lactobacillus rossiae</i>	DSM-15814	Food	
<i>Lactobacillus sakei carnosus</i>	DSM-15831	Food	
<i>Lactobacillus sanfranciscensis</i>	DSM-20451	Food	
<i>Lactobacillus secaliphilus</i>	DSM-17896	Food	
<i>Lactobacillus selangorensis</i>	DSM-13344	Food	
<i>Lactobacillus selangorensis</i>	ATCC-BAA-66	Food	
<i>Lactobacillus senmaizukei</i>	DSM-21775	Food	
<i>Lactobacillus siliginis</i>	DSM-22696	Food	
<i>Lactobacillus spicheri</i>	DSM-15429	Food	
<i>Lactobacillus suebicus</i>	DSM-5007	Food	
<i>Lactobacillus sunkii</i>	DSM-19904	Food	
<i>Lactobacillus tucseti</i>	DSM-20183	Food	
<i>Lactobacillus versmoldensis</i>	DSM-14857	Food	
<i>Lactobacillus xiangfangensis</i>	LMG-26013	Food	
<i>Lactobacillus zymae</i>	DSM-19395	Food	
<i>Lactococcus lactis</i>	LMG-7760	Food	
<i>Leuconostoc argentinum</i>	KCTC-3773	Food	Yes
<i>Leuconostoc carnosum</i>	JB16	Food	
<i>Leuconostoc citreum</i>	KM20	Food	
<i>Leuconostoc fallax</i>	KCTC-3537	Food	Yes
<i>Leuconostoc gasicomitatum</i>	LMG-18811	Food	
<i>Leuconostoc gelidum</i>	KCTC-3527	Food	Yes
<i>Leuconostoc kimchii</i>	IMSNU-11154	Food	
<i>Leuconostoc mesenteroides</i>	ATCC-8293	Food	
<i>Leuconostoc pseudomesenteroides</i>	4882	Food	
<i>Pediococcus argentinicus</i>	DSM-23026	Food	
<i>Weissella halotolerans</i>	DSM-20190	Food	
<i>Weissella minor</i>	DSM-20014	Food	
<i>Weissella viridescens</i>	DSM-20410	Food	

Supplementary Table 1. Continued

<i>Atopobium minutum</i>	DSM-20586	Human/Animal	
<i>Atopobium rimae</i>	DSM-7090	Human/Animal	
<i>Carnobacterium maltaromaticum</i>	DSM-20730	Human/Animal	Yes
<i>Kandleria vitulina</i>	DSM-20405	Human/Animal	Yes
<i>Lactobacillus acidophilus</i>	DSM-20079	Human/Animal	Yes
<i>Lactobacillus amylophilus</i>	DSM-20533	Human/Animal	Yes
<i>Lactobacillus amylophilus</i>	DSM-20534	Human/Animal	
<i>Lactobacillus amylovorus</i>	DSM-20531	Human/Animal	Yes
<i>Lactobacillus amylovorus</i>	DSM-16698	Human/Animal	Yes
<i>Lactobacillus animalis</i>	DSM-20602	Human/Animal	
<i>Lactobacillus antri</i>	DSM-16041	Human/Animal	
<i>Lactobacillus apodemi</i>	DSM-16634	Human/Animal	Yes
<i>Lactobacillus aviarius araffinosus</i>	DSM-20653	Human/Animal	
<i>Lactobacillus aviarius aviarius</i>	DSM-20655	Human/Animal	
<i>Lactobacillus brantae</i>	DSM-23927	Human/Animal	
<i>Lactobacillus brevis</i>	DSM-20054	Human/Animal	
<i>Lactobacillus ceti</i>	DSM-22408	Human/Animal	
<i>Lactobacillus coleohominis</i>	DSM-14060	Human/Animal	
<i>Lactobacillus crispatus</i>	DSM-20584	Human/Animal	Yes
<i>Lactobacillus equi</i>	DSM-15833	Human/Animal	
<i>Lactobacillus equicursoris</i>	DSM-19284	Human/Animal	Yes
<i>Lactobacillus equigenerosi</i>	DSM-18793	Human/Animal	
<i>Lactobacillus fermentum</i>	DSM-20055	Human/Animal	
<i>Lactobacillus gallinarum</i>	DSM-10532	Human/Animal	Yes
<i>Lactobacillus gasseri</i>	ATCC-33323	Human/Animal	
<i>Lactobacillus gastricus</i>	DSM-16045	Human/Animal	Yes
<i>Lactobacillus gigeriorum</i>	DSM-23908	Human/Animal	Yes
<i>Lactobacillus hamsteri</i>	DSM-5661	Human/Animal	Yes
<i>Lactobacillus hayakitensis</i>	DSM-18933	Human/Animal	
<i>Lactobacillus hominis</i>	DSM-23910	Human/Animal	Yes
<i>Lactobacillus iners</i>	DSM-13335	Human/Animal	
<i>Lactobacillus ingluviei</i>	DSM-15946	Human/Animal	
<i>Lactobacillus ingluviei</i>	DSM-14792	Human/Animal	
<i>Lactobacillus intestinalis</i>	DSM-6629	Human/Animal	Yes
<i>Lactobacillus jensenii</i>	DSM-20557	Human/Animal	
<i>Lactobacillus johnsonii</i>	ATCC-33200	Human/Animal	Yes
<i>Lactobacillus kalixensis</i>	DSM-16043	Human/Animal	Yes
<i>Lactobacillus kitasatonis</i>	DSM-16761	Human/Animal	Yes
<i>Lactobacillus mucosae</i>	DSM-13345	Human/Animal	
<i>Lactobacillus murinus</i>	DSM-20452	Human/Animal	Yes
<i>Lactobacillus oligofermentans</i>	DSM-15707	Human/Animal	
<i>Lactobacillus oris</i>	DSM-4864	Human/Animal	
<i>Lactobacillus pantheris</i>	DSM-15945	Human/Animal	
<i>Lactobacillus parabuchneri</i>	DSM-5707	Human/Animal	Yes
<i>Lactobacillus psittaci</i>	DSM-15354	Human/Animal	
<i>Lactobacillus rennini</i>	DSM-20253	Human/Animal	

Supplementary Table 1. Continued

<i>Lactobacillus reuteri</i>	DSM-20016	Human/Animal	
<i>Lactobacillus ruminis</i>	DSM-20403	Human/Animal	
<i>Lactobacillus saerimneri</i>	DSM-16049	Human/Animal	
<i>Lactobacillus salivarius</i>	DSM-20555	Human/Animal	
<i>Lactobacillus saniviri</i>	DSM-24301	Human/Animal	
<i>Lactobacillus senioris</i>	DSM-24302	Human/Animal	
<i>Lactobacillus ultunensis</i>	DSM-16047	Human/Animal	Yes
<i>Lactobacillus vaccinostrercus</i>	DSM-20634	Human/Animal	
<i>Lactobacillus vaginalis</i>	DSM-5837	Human/Animal	
<i>Olsenella uli</i>	DSM-7084	Human/Animal	
<i>Fructobacillus fructosus</i>	DSM-20349	Plant	
<i>Lactobacillus buchneri</i>	DSM-20057	Plant	
<i>Lactobacillus cacaonum</i>	DSM-21116	Plant	
<i>Lactobacillus camelliae</i>	DSM-22697	Plant	
<i>Lactobacillus coryniformis coryniformis</i>	DSM-20001	Plant	
<i>Lactobacillus dextrinicus</i>	DSM-20335	Plant	
<i>Lactobacillus diolivorans</i>	DSM-14421	Plant	
<i>Lactobacillus fabifermentans</i>	DSM-21115	Plant	
<i>Lactobacillus floricola</i>	DSM-23037	Plant	
<i>Lactobacillus florum</i>	DSM-22689	Plant	
<i>Lactobacillus ghanensis</i>	DSM-18630	Plant	
<i>Lactobacillus graminis</i>	DSM-20719	Plant	Yes
<i>Lactobacillus hokkaidonensis</i>	DSM-26202	Plant	Yes
<i>Lactobacillus hordei</i>	DSM-19519	Plant	Yes
<i>Lactobacillus manihotivorans</i>	DSM-13343	Plant	
<i>Lactobacillus nasuensis</i>	JCM-17158	Plant	
<i>Lactobacillus ozensis</i>	DSM-23829	Plant	
<i>Lactobacillus plantarum</i>	DSM-13273	Plant	Yes
<i>Lactobacillus plantarum argentoratensis</i>	DSM-16365	Plant	
<i>Lactobacillus pobuzihii</i>	NBRC-103219	Plant	
<i>Lactobacillus pobuzihii.Chen</i>	KCTC-13174	Plant	
<i>Lactobacillus sucicola</i>	DSM-21376	Plant	
<i>Lactobacillus taiwanensis</i>	DSM-21401	Plant	Yes
<i>Lactobacillus thailandensis</i>	DSM-22698	Plant	
<i>Lactobacillus uvarum</i>	DSM-19971	Plant	
<i>Lactobacillus vini</i>	DSM-20605	Plant	
<i>Pediococcus lolii</i>	DSM-19927	Plant	
<i>Pediococcus parvulus</i>	DSM-20332	Plant	
<i>Pediococcus stilesii</i>	DSM-18001	Plant	
<i>Weissella confusa</i>	DSM-20196	Plant	
<i>Lactobacillus fructivorans</i>	DSM-20203	Unknown	
<i>Lactobacillus paracasei paracasei</i>	DSM-5622	Unknown	Yes
<i>Lactobacillus pasteurii</i>	DSM-23907	Unknown	Yes
<i>Lactobacillus pentosus</i>	DSM-20314	Unknown	Yes
<i>Lactobacillus rhamnosus</i>	DSM-20021	Unknown	Yes
<i>Leuconostoc mesenteroides cremoris</i>	ATCC-19254	Unknown	

Supplementary Table 1. Continued

<i>Pediococcus acidilactici</i>	AS1-2696	Unknown	
<i>Lactobacillus amylolyticus</i>	DSM-11664	Wine/Alcohol Products	Yes
<i>Lactobacillus composti</i>	DSM-18527	Wine/Alcohol Products	
<i>Lactobacillus delbrueckii jakobsenii</i>	DSM-26046	Wine/Alcohol Products	
<i>Lactobacillus farraginis</i>	DSM-18382	Wine/Alcohol Products	Yes
<i>Lactobacillus fructivorans</i>	ATCC-27394	Wine/Alcohol Products	
<i>Lactobacillus fructivorans</i>	DSM-20350	Wine/Alcohol Products	
<i>Lactobacillus helveticus</i>	LMG-22464	Wine/Alcohol Products	Yes
<i>Lactobacillus hilgardii</i>	DSM-20176	Wine/Alcohol Products	
<i>Lactobacillus homohiochii</i>	DSM-20571	Wine/Alcohol Products	
<i>Lactobacillus kunkeei</i>	DSM-12361	Wine/Alcohol Products	
<i>Lactobacillus lindneri</i>	DSM-20690	Wine/Alcohol Products	
<i>Lactobacillus malefermentans</i>	DSM-5705	Wine/Alcohol Products	
<i>Lactobacillus mali</i>	DSM-20444	Wine/Alcohol Products	
<i>Lactobacillus mali</i>	ATCC-27304	Wine/Alcohol Products	
<i>Lactobacillus nagelii</i>	DSM-13675	Wine/Alcohol Products	
<i>Lactobacillus oeni</i>	DSM-19972	Wine/Alcohol Products	
<i>Lactobacillus parabuchneri</i>	DSM-15352	Wine/Alcohol Products	
<i>Lactobacillus parafarraginis</i>	DSM-18390	Wine/Alcohol Products	Yes
<i>Lactobacillus paralimentarius</i>	DSM-19674	Wine/Alcohol Products	
<i>Lactobacillus paraplantarum</i>	DSM-10667	Wine/Alcohol Products	Yes
<i>Lactobacillus paucivorans</i>	DSM-22467	Wine/Alcohol Products	
<i>Lactobacillus sakei sakei</i>	DSM-20017	Wine/Alcohol Products	
<i>Lactobacillus satsumensis</i>	DSM-16230	Wine/Alcohol Products	
<i>Lactobacillus similis</i>	DSM-23365	Wine/Alcohol Products	
<i>Lactobacillus zeae</i>	DSM-20178	Wine/Alcohol Products	Yes
<i>Oenococcus kitaharae</i>	DSM-17330	Wine/Alcohol Products	
<i>Oenococcus oeni</i>	ATCC-BAA-1163	Wine/Alcohol Products	Yes
<i>Pediococcus cellicola</i>	DSM-17757	Wine/Alcohol Products	
<i>Pediococcus claussenii</i>	DSM-14800	Wine/Alcohol Products	Yes
<i>Pediococcus damnosus</i>	DSM-20331	Wine/Alcohol Products	Yes
<i>Pediococcus ethanolidurans</i>	DSM-22301	Wine/Alcohol Products	
<i>Pediococcus inopinatus</i>	DSM-20285	Wine/Alcohol Products	
<i>Pediococcus pentosaceus</i>	DSM-20336	Wine/Alcohol Products	

Supplementary Table 2. Bacterial strains screened for bacteriocin production

Species	Strain	Growth Medium	Condition	Temp (°C)
<i>Carnobacterium maltaromaticum</i>	DSM 20342	TSA	Aerobic	30
<i>Carnobacterium maltaromaticum</i>	DSM 20722	TSA	Aerobic	30
<i>Carnobacterium maltaromaticum</i>	DSM 20730	TSA	Aerobic	30
<i>Lactobacillus acidipiscis</i>	DSM 15836	MRS + Vitamin soln.	Anaerobic	30
<i>Lactobacillus acidophilus</i>	DSM 20079	mMRS	Anaerobic	37
<i>Lactobacillus agilis</i>	DSM 20509	mMRS	Anaerobic	38
<i>Lactobacillus amylophilus</i>	DSM 20533	MRS	Aerobic	30
<i>Lactobacillus amylovorus</i>	DSM 16698	MRS	Anaerobic	37
<i>Lactobacillus amylovorus</i>	DSM 20531	MRS	Anaerobic	37
<i>Lactobacillus apodemi</i>	DSM 16634	MRS	Anaerobic	37
<i>Lactobacillus aquaticus</i>	DSM 21051	MRS	Anaerobic	37
<i>Lactobacillus buchneri</i>	DSM 20057	MRS	Aerobic	37
<i>Lactobacillus casei</i>	DSM 20011	MRS	Aerobic	30
<i>Lactobacillus composti</i>	DSM 18527	MRS	Anaerobic	30
<i>Lactobacillus coryniformis</i> subsp. <i>coryniformis</i>	DSM 20001	MRS	Aerobic	30
<i>Lactobacillus coryniformis</i> subsp. <i>torquens</i>	DSM 20004	MRS	Aerobic	30
<i>Lactobacillus crispatus</i>	DSM 20584	mMRS	Anaerobic	37
<i>Lactobacillus equicursoris</i>	DSM 19284	MRS	Anaerobic	37
<i>Lactobacillus fabifermentans</i>	DSM 21115	MRS	Anaerobic	30
<i>Lactobacillus fuchuensis</i>	DSM 14340	MRS	Aerobic	20
<i>Lactobacillus futsaii</i>	JCM 17355	MRS	Aerobic	30
<i>Lactobacillus gastricus</i>	DSM 16045	MRS	Anaerobic	37
<i>Lactobacillus graminis</i>	DSM 16045	MRS	Aerobic	30
<i>Lactobacillus hamsteri</i>	DSM 5661	MRS	Anaerobic	37
<i>Lactobacillus harbinensis</i>	DSM 16991	MRS	Anaerobic	37
<i>Lactobacillus helveticus</i>	CGMCC 1.1877	MRS	Anaerobic	37
<i>Lactobacillus helveticus</i>	LMG 22464	MRS	Anaerobic	37
<i>Lactobacillus hokkaidonensis</i>	DSM 26202	MRS	Anaerobic	25
<i>Lactobacillus hordei</i>	DSM 19519	MRS	Anaerobic	30
<i>Lactobacillus intestinalis</i>	DSM 6629	MRS	Aerobic	37
<i>Lactobacillus johnsoni</i>	DSM 10533	MRS	Anaerobic	37
<i>Lactobacillus kalixensis</i>	DSM 16043	MRS	Aerobic	37
<i>Lactobacillus kimchicus</i>	JCM 15530	MRS	Aerobic	37

Supplementary Table 2. Continued

Species	Strain	Growth Medium	Condition	Temp (°C)
<i>Lactobacillus kimchiensis</i>	DSM 24716	MRS	Anaerobic	25
<i>Lactobacillus kitasatonis</i>	DSM 16761	MRS	Anaerobic	37
<i>Lactobacillus mali</i>	DSM 20444	MRS	Aerobic	30
<i>Lactobacillus mindensis</i>	DSM 14500	MRS	Anaerobic	30
<i>Lactobacillus murinus</i>	DSM 20452	MRS	Aerobic	37
<i>Lactobacillus nantensis</i>	DSM 16982	mMRS + 1% maltose + 0.5% YE	Aerobic	30
<i>Lactobacillus nodensis</i>	DSM 19682	MRS	Anaerobic	30
<i>Lactobacillus otakiensis</i>	DSM 19908	MRS	Anaerobic	30
<i>Lactobacillus parabuchneri</i>	DSM 5707	MRS	Aerobic	30
<i>Lactobacillus paracasei</i> subsp. <i>paracasei</i>	DSM 5622	MRS	Aerobic	30
<i>Lactobacillus paracasei</i> subsp. <i>tolerans</i>	DSM 20258	MRS	Aerobic	30
<i>Lactobacillus parafarraginis</i>	DSM 18390	MRS	Anaerobic	30
<i>Lactobacillus paralimentarius</i>	DSM 13961	MRS	Aerobic	30
<i>Lactobacillus paralimentarius</i>	DSM 13238	MRS	Aerobic	30
<i>Lactobacillus paraplantarum</i>	DSM 10667	MRS	Aerobic	30
<i>Lactobacillus pasteurii</i>	DSM 23907	MRS	Anaerobic	37
<i>Lactobacillus pentosus</i>	DSM 20314	MRS	Aerobic	30
<i>Lactobacillus plantarum</i>	DSM 13273	MRS	Aerobic	37
<i>Lactobacillus plantarum</i> subsp. <i>argenterotensis</i>	DSM 16365	MRS	Anaerobic	30
<i>Lactobacillus plantarum</i> subsp. <i>plantarum</i>	DSM 20174	MRS	Aerobic	30
<i>Lactobacillus rennini</i>	DSM 20253	MRS + CAA	Aerobic	30
<i>Lactobacillus reuteri</i>	DSM 20016	MRS	Aerobic	37
<i>Lactobacillus rhamnosus</i>	DSM 20021	MRS	Aerobic	37
<i>Lactobacillus rossiae</i>	DSM 15814	MRS + 1% maltose + 1% YE	Anaerobic	30
<i>Lactobacillus ruminis</i>	DSM 20403	MRS	Anaerobic	37
<i>Lactobacillus similis</i>	DSM 23365	MRS	Anaerobic	37
<i>Lactobacillus taiwanensis</i>	DSM 21401	MRS	Anaerobic	37
<i>Lactobacillus xiangfangensis</i>	LMG 26013	MRS	Aerobic	30
<i>Lactobacillus zeae</i>	DSM 20178	MRS	Aerobic	37
<i>Leuconostoc fallax</i>	DSM 20189	MRS	Aerobic	30
<i>Leuconostoc gasicomitatum</i>	LMG 18811	MRS	Anaerobic	22
<i>Leuconostoc gelidum</i> subsp. <i>gelidum</i>	DSM 5578	MRS	Anaerobic	25
<i>Leuconostoc lactis</i>	DSM 8581	MRS	Aerobic	30

Supplementary Table 2. Continued

Species	Strain	Growth Medium	Condition	Temp (°C)
<i>Oenococcus kitaharae</i>	DSM 17330	mMRS + 10% tomato juice	Anaerobic	30
<i>Oenococcus oeni</i>	ATCC-BAA 1163	MRS	Anaerobic	37
<i>Pediococcus cellicola</i>	DSM 17757	MRS	Anaerobic	30
<i>Pediococcus claussenii</i>	DSM 14800	MRS pH 5.7	Aerobic	30
<i>Pediococcus damnosus</i>	DSM 20331	mMRS pH 5.7	Anaerobic	26
<i>Pediococcus ethanolidurans</i>	DSM 22301	MRS	Anaerobic	37
<i>Pediococcus pentosaceus</i>	DSM 20336	MRS	Aerobic	30
<i>Pediococcus stilesii</i>	DSM 18001	MRS	Anaerobic	30

Supplementary Table 3. Indicator Strains

Species	Strain	Growth Medium	Conditions	Temp (°C)
<i>Enterococcus faecium</i>	LMG 11423	MRS	Anaerobic	37
<i>E. mundtii</i>	LMG 10748	MRS	Anaerobic	37
<i>E. saccharolyticus</i>	LMG 11427	MRS	Anaerobic	37
<i>Lactobacillus acidophilus</i>	LMG 9433	MRS	Anaerobic	37
<i>L. agilis</i>	LMG 9186	MRS	Anaerobic	37
<i>L. amylovorus</i>	LMG 9496	MRS	Anaerobic	37
<i>L. casei</i>	LMG 6904	mMRS	Anaerobic	37
<i>L. crispatus</i>	LMG 9479	MRS	Anaerobic	37
<i>L. delbrueckii</i> subsp. <i>bulgaricus</i>	LMG 6901	MRS	Anaerobic	37
<i>L. delbrueckii</i> subsp. <i>lactis</i>	LMG 7942	MRS	Anaerobic	37
<i>L. fermentum</i>	LMG 6902	MRS	Anaerobic	37
<i>L. johnsonii</i>	DSM 10533	MRS	Anaerobic	37
<i>L. plantarum</i>	LMG 6907	MRS	Anaerobic	37
<i>L. rhamnosus</i>	GG	MRS	Anaerobic	37
<i>Listeria innocua</i>	DPC 3572	BHI	Aerobic	37
<i>Micrococcus luteus</i>	DPC 6275	BHI	Aerobic	30
<i>Staphylococcus aureus</i>	DPC 5246	BHI	Aerobic	37
<i>Salmonella typhimurium</i>	LT2	BHI	Aerobic	37

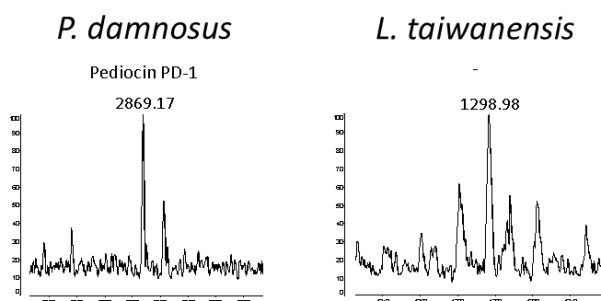
Supplementary Figure 1. Divergence and percentage identity of helveticin homologs encoded by *Lactobacillus* species (Clustal ω)

Divergence

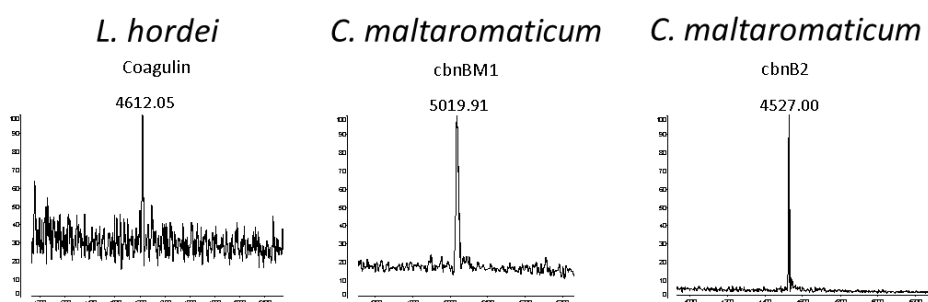
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Supplementary Figure 2. Colony MALDI TOF MS and SDS PAGE profiles of the peptides produced by the cells indicate the mass and identity of each bacteriocin produced

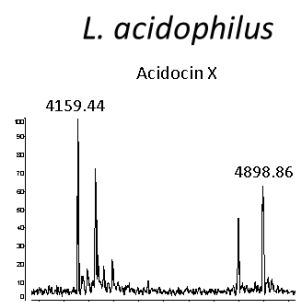
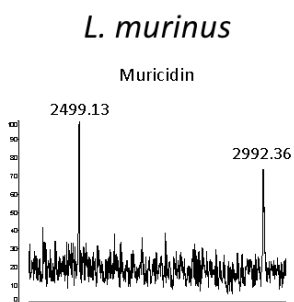
Class I



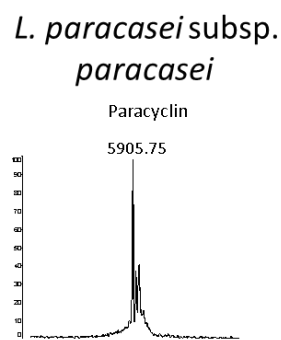
Class IIa



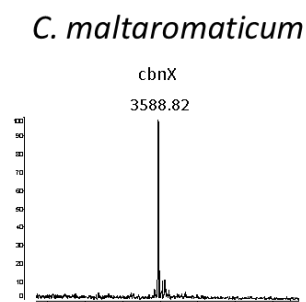
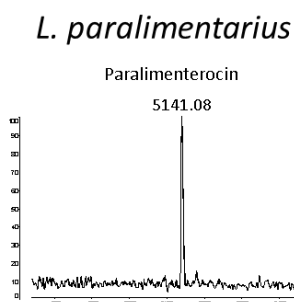
Class IIb



Class IIc



Class II d



L. equicursoris

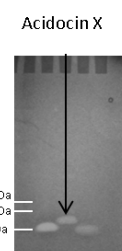
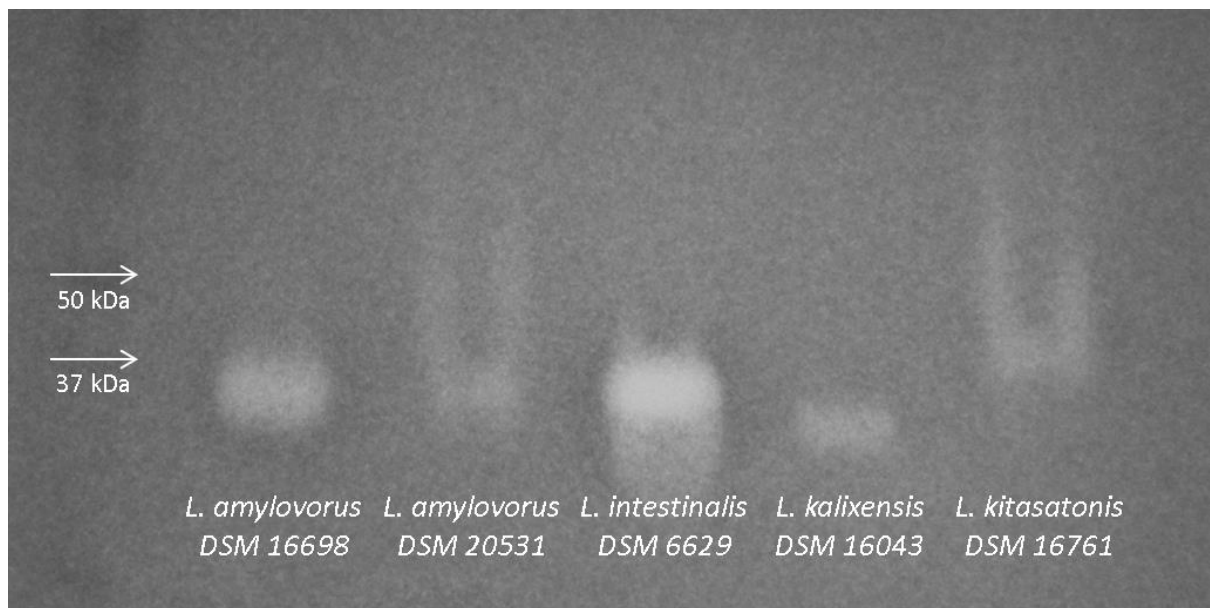


Figure 3. An SDS PAGE gel overlayed with the indicator *L. delbrueckii* subsp. *bulgaricus* shows the mass of the antimicrobial helveticin-like peptides produced by these lactobacilli.



References

- ACEDO, J. Z., VAN BELKUM, M. J., LOHANS, C. T., MCKAY, R. T., MISKOLZIE, M. & VEDERAS, J. C. 2015. Solution structure of acidocin B, a circular bacteriocin produced by *Lactobacillus acidophilus* M46. *Applied and Environmental Microbiology*, 81, 2910-2918.
- ANASTASIADOU, S., PAPAGIANNI, M., FILIOUSIS, G., AMBROSIADIS, I. & KOIDIS, P. 2008a. Growth and metabolism of a meat isolated strain of *Pediococcus pentosaceus* in submerged fermentation: Purification, characterization and properties of the produced pediocin SM-1. *Enzyme and Microbial Technology*, 43, 448-454.
- ANASTASIADOU, S., PAPAGIANNI, M., FILIOUSIS, G., AMBROSIADIS, I. & KOIDIS, P. 2008b. Pediocin SA-1, an antimicrobial peptide from *Pediococcus acidilactici* NRRL B5627: Production conditions, purification and characterization. *Bioresource Technology*, 99, 5384-5390.
- ARAKAWA, K., KAWAI, Y., ITO, Y., NAKAMURA, K., CHUJO, T., NISHIMURA, J., KITAZAWA, H. & SAITO, T. 2010. HPLC purification and re-evaluation of chemical identity of two circular bacteriocins, gassericin A and reuterin 6. *Letters in Applied Microbiology*, 50, 406-411.
- ATRIH, A., REKHIF, N., MOIR, A. J., LEBRIHI, A. & LEFEBVRE, G. 2001. Mode of action, purification and amino acid sequence of plantaricin C19, an anti-*Listeria* bacteriocin produced by *Lactobacillus plantarum* C19. *International Journal of Food Microbiology*, 68, 93-104.
- AYMERICH, M. T., GARRIGA, M., MONFORT, J. M., NES, I. & HUGAS, M. 2000. Bacteriocin-producing lactobacilli in Spanish-style fermented sausages: Characterization of bacteriocins. *Food Microbiology*, 17, 33-45.
- BAREFOOT, S. F. & KLAENHAMMER, T. R. 1983. Detection and activity of lactacin B, a bacteriocin produced by *Lactobacillus acidophilus*. *Applied and Environmental Microbiology*, 45, 1808-1815.
- BARRETT, E., HAYES, M., O'CONNOR, P., GARDINER, G., FITZGERALD, G. F., STANTON, C., ROSS, R. P. & HILL, C. 2007. Salivaricin P, one of a family of two-component antilisterial bacteriocins produced by intestinal isolates of *Lactobacillus salivarius*. *Applied and Environmental Microbiology*, 73, 3719-23.
- BAUER, R., CHIKINDAS, M. L. & DICKS, L. M. 2005. Purification, partial amino acid sequence and mode of action of pediocin PD-1, a bacteriocin produced by *Pediococcus damnosus* NCFB 1832. *International Journal of Food Microbiology*, 101, 17-27.
- BEGLEY, M., COTTER, P. D., HILL, C. & ROSS, R. P. 2009. Identification of a Novel Two-Peptide Lantibiotic, Lichenicidin, following Rational Genome Mining for LanM Proteins. *Applied and Environmental Microbiology*, 75, 5451-5460.
- BENOIT, V., LEBRIHI, A., MILLIERE, J. B. & LEFEBVRE, G. 1997. Purification and partial amino acid sequence of brevicin 27, a bacteriocin produced by *Lactobacillus brevis* SB27. *Current Microbiology*, 34, 173-9.
- BUDDE, B. B., HORNBAEK, T., JACOBSEN, T., BARKHOLT, V. & KOCH, A. G. 2003. *Leuconostoc carnosum* 4010 has the potential for use as a protective culture for vacuum-packed meats: culture isolation, bacteriocin identification, and meat application experiments. *International Journal of Food Microbiology*, 83, 171-184.
- BUSARCEVIC, M. & DALGALARRONDO, M. 2012. Purification and genetic characterisation of the novel bacteriocin LS2 produced by the human oral strain *Lactobacillus salivarius* BGH01. *International Journal of Antimicrobial Agents*, 40, 127-134.
- CHEN, Y.-S., WANG, Y.-C., CHOW, Y.-S., YANAGIDA, F., LIAO, C.-C. & CHIU, C.-M. 2014. Purification and characterization of plantaricin Y, a novel bacteriocin produced by *Lactobacillus plantarum* 510. *Archives of Microbiology*, 196, 193-199.
- COCOLIN, L. & RANTSIOU, K. 2007. Sequencing and expression analysis of sakacin genes in *Lactobacillus curvatus* strains. *Applied Microbiology and Biotechnology*, 76, 1403-11.
- CONTRERAS, B., DE VUYST, L., DEVREESE, B., BUSANYOVA, K., RAYMAECKERS, J., BOSMAN, F., SABLON, E. & VANDAMME, E. 1997. Isolation, purification, and amino acid sequence of

- lactobin A, one of the two bacteriocins produced by *Lactobacillus amylovorus* LMG P-13139. *Applied and Environmental Microbiology*, 63, 13-20.
- COTTER, P. D., HILL, C. & ROSS, R. P. 2005. Bacteriocins: developing innate immunity for food. *Nature Reviews Microbiology*, 3, 777-88.
- COTTER, P. D., ROSS, R. P. & HILL, C. 2013. Bacteriocins - a viable alternative to antibiotics? *Nature Reviews Microbiology*, 11, 95-105.
- DE JONG, A., VAN HEEL, A. J., KOK, J. & KUIPERS, O. P. 2010. BAGEL2: mining for bacteriocins in genomic data. *Nucleic Acids Research*, 38, W647-51.
- DE VUYST, L., AVONTS, L., NEYSENS, P., HOSTE, B., VANCANNEYT, M., SWINGS, J. & CALLEWAERT, R. 2004. The lactobin A and amylovorin L471 encoding genes are identical, and their distribution seems to be restricted to the species *Lactobacillus amylovorus* that is of interest for cereal fermentations. *International Journal of Food Microbiology*, 90, 93-106.
- DIEP, D. B., AXELSSON, L., GREFSLI, C. & NES, I. F. 2000. The synthesis of the bacteriocin sakacin A is a temperature-sensitive process regulated by a pheromone peptide through a three-component regulatory system. *Microbiology*, 146 (Pt 9), 2155-60.
- DIEP, D. B., GODAGER, L., BREDE, D. & NES, I. F. 2006. Data mining and characterization of a novel pediocin-like bacteriocin system from the genome of *Pediococcus pentosaceus* ATCC 25745. *Microbiology*, 152, 1649-1659.
- DIEP, D. B., HÅVARSTEIN, L. S. & NES, I. F. 1996. Characterization of the locus responsible for the bacteriocin production in *Lactobacillus plantarum* C11. *Journal of Bacteriology*, 178, 4472-4483.
- DIMITRIJEVIC, R., STOJANOVIC, M., ZIVKOVIC, I., PETERSEN, A., JANKOV, R. M., DIMITRIJEVIC, L. & GAVROVIC-JANKULOVIC, M. 2009. The identification of a low molecular mass bacteriocin, rhamnosin A, produced by *Lactobacillus rhamnosus* strain 68. *Journal of Applied Microbiology*, 107, 2108-15.
- DOBSON, A., COTTER, P. D., ROSS, R. P. & HILL, C. 2012. Bacteriocin production: a probiotic trait? *Applied and Environmental Microbiology*, 78, 1-6.
- ENNAHAR, S., AOUDE-WERNER, D., SOROKINE, O., VAN DORSELAER, A., BRINGEL, F., HUBERT, J.-C. & HASSELMANN, C. 1996. Production of pediocin AcH by *Lactobacillus plantarum* WHE 92 isolated from cheese. *Applied and Environmental Microbiology*, 62, 4381-4387.
- FELIX, J. V., PAPATHANASOPOULOS, M. A., SMITH, A. A., VON HOLY, A. & HASTINGS, J. W. 1994. Characterization of leucocin B-Ta11a: A bacteriocin from *Leuconostoc carnosum* Ta11a isolated from meat. *Current microbiology*, 29, 207-212.
- FIELD, D., QUIGLEY, L., O'CONNOR, P. M., REA, M. C., DALY, K., COTTER, P. D., HILL, C. & ROSS, R. P. 2010. Studies with bioengineered Nisin peptides highlight the broad-spectrum potency of Nisin V. *Microbial Biotechnology*, 3, 473-86.
- FIMLAND, G., JOHNSEN, L., DALHUS, B. & NISSEN-MEYER, J. 2005. Pediocin-like antimicrobial peptides (class IIa bacteriocins) and their immunity proteins: biosynthesis, structure, and mode of action. *Journal of Peptide Science*, 11, 688-96.
- FLUHE, L., KNAPPE, T. A., GATTNER, M. J., SCHAFER, A., BURGHAEUS, O., LINNE, U. & MARAHIEL, M. A. 2012. The radical SAM enzyme AlbA catalyzes thioether bond formation in subtilisin A. *Nature Chemical Biology*, 8, 350-7.
- FLYNN, S., VAN SINDEREN, D., THORNTON, G. M., HOLO, H., NES, I. F. & COLLINS, J. K. 2002. Characterization of the genetic locus responsible for the production of ABP-118, a novel bacteriocin produced by the probiotic bacterium *Lactobacillus salivarius* subsp. *salivarius* UCC118. *Microbiology*, 148, 973-84.
- FREMAUX, C., AHN, C. & KLAENHAMMER, T. R. 1993. Molecular analysis of the lactacin F operon. *Applied and Environmental Microbiology*, 59, 3906-15.
- FRICOURT, B. V., BAREFOOT, S. F., TESTIN, R. F. & HAYASAKA, S. S. 1994. Detection and Activity of Plantaricin-F an Antibacterial Substance from *Lactobacillus-Plantarum* Bf001 Isolated from Processed Channel Catfish. *Journal of Food Protection*, 57, 698-702.
- GABRIELSEN, C., BREDE, D. A., NES, I. F. & DIEP, D. B. 2014. Circular bacteriocins: biosynthesis and mode of action. *Applied and Environmental Microbiology*, 80, 6854-62.

- GARVER, K. I. & MURIANA, P. M. 1994. Purification and Partial Amino-Acid-Sequence of Curvaticin Fs47, a Heat-Stable Bacteriocin Produced by *Lactobacillus-Curvatus* Fs47. *Applied and Environmental Microbiology*, 60, 2191-2195.
- GHALFI, H., BENKERROUM, N., ONGENA, M., BENSALD, M. & THONART, P. 2010. Production of three anti-listerial peptides by *Lactobacillus curvatus* in MRS broth. *Food Research International*, 43, 33-39.
- GILLOR, O., ETZION, A. & RILEY, M. 2008. The dual role of bacteriocins as anti-and probiotics. *Applied Microbiology and Biotechnology*, 81, 591-606.
- GILLOR, O., GILADI, I. & RILEY, M. A. 2009. Persistence of colicinogenic *Escherichia coli* in the mouse gastrointestinal tract. *BMC Microbiology*, 9, 165.
- GONZALEZ, B., ARCA, P., MAYO, B. & SUAREZ, J. E. 1994. Detection, purification, and partial characterization of plantaricin C, a bacteriocin produced by a *Lactobacillus plantarum* strain of dairy origin. *Applied and Environmental Microbiology*, 60, 2158-63.
- GONZALEZ, C. F. & KUNKA, B. S. 1987. Plasmid-associated bacteriocin production and sucrose fermentation in *Pediococcus acidilactici*. *Applied and Environmental Microbiology*, 53, 2534-2538.
- GOTO, Y., LI, B., CLAESEN, J., SHI, Y., BIBB, M. J. & VAN DER DONK, W. A. 2010. Discovery of unique lanthionine synthetases reveals new mechanistic and evolutionary insights. *PLoS Biology*, 8, e1000339.
- GREEN, G., DICKS, L. M., BRUGGEMAN, G., VANDAMME, E. J. & CHIKINDAS, M. L. 1997. Pediocin PD-1, a bactericidal antimicrobial peptide from *Pediococcus damnosus* NCFB 1832. *Journal of Applied Microbiology*, 83, 127-32.
- HAFT, D. H. 2009. A strain-variable bacteriocin in *Bacillus anthracis* and *Bacillus cereus* with repeated Cys-Xaa-Xaa motifs. *Biology Direct*, 4, 15.
- HASTINGS, J., SAILER, M., JOHNSON, K., ROY, K., VEDERAS, J. & STILES, M. 1991. Characterization of leucocin A-UAL 187 and cloning of the bacteriocin gene from *Leuconostoc gelidum*. *Journal of Bacteriology*, 173, 7491-7500.
- HATA, T., TANAKA, R. & OHMOMO, S. 2010. Isolation and characterization of plantaricin ASM1: a new bacteriocin produced by *Lactobacillus plantarum* A-1. *International Journal of Food Microbiology*, 137, 94-9.
- HEBERT, E. M., SAAVEDRA, L., TARANTO, M. P., MOZZI, F., MAGNI, C., NADER, M. E. F., DE VALDEZ, G. F., SESMA, F., VIGNOLO, G. & RAYA, R. R. 2012. Genome sequence of the bacteriocin-producing *Lactobacillus curvatus* strain CRL705. *Journal of Bacteriology*, 194, 538-539.
- HÉCHARD, Y., BERJEAUD, J.-M. & CENATTEMPO, Y. 1999. Characterization of the mesB gene and expression of bacteriocins by *Leuconostoc mesenteroides* Y105. *Current Microbiology*, 39, 265-269.
- HECHARD, Y., DERIJARD, B., LETELLIER, F. & CENATTEMPO, Y. 1992. Characterization and purification of mesentericin Y105, an anti-*Listeria* bacteriocin from *Leuconostoc mesenteroides*. *Journal of General Microbiology*, 138, 2725-31.
- HEQUET, A., LAFFITTE, V., SIMON, L., DE SOUSA-CAETANO, D., THOMAS, C., FREMAUX, C. & BERJEAUD, J. M. 2007. Characterization of new bacteriocinogenic lactic acid bacteria isolated using a medium designed to simulate inhibition of *Listeria* by *Lactobacillus sakei* 2512 on meat. *International Journal of Food Microbiology*, 113, 67-74.
- HOLCK, A., AXELSSON, L., BIRKELAND, S. E., AUKRUST, T. & BLOM, H. 1992. Purification and amino acid sequence of sakacin A, a bacteriocin from *Lactobacillus sake* Lb706. *J Gen Microbiol*, 138, 2715-20.
- HOLCK, A. L., AXELSSON, L., HÜHNE, K. & KRÖCKEL, L. 1994. Purification and cloning of sakacin 674, a bacteriocin from *Lactobacillus sake* Lb674. *FEMS Microbiology Letters*, 115, 143-149.
- HOLO, H., JEKNIC, Z., DAESCHEL, M., STEVANOVIC, S. & NES, I. F. 2001. Plantaricin W from *Lactobacillus plantarum* belongs to a new family of two-peptide lantibiotics. *Microbiology*, 147, 643-51.

- HU, M., ZHAO, H., ZHANG, C., YU, J. & LU, Z. 2013. Purification and characterization of plantaricin 163, a novel bacteriocin produced by *Lactobacillus plantarum* 163 isolated from traditional Chinese fermented vegetables. *Journal of Agricultural and Food Chemistry*, 61, 11676-82.
- HUGAS, M., GARRIGA, M., AYMERICH, M. & MONFORT, J. 1995. Inhibition of *Listeria* in dry fermented sausages by the bacteriocinogenic *Lactobacillus sake* CTC494. *Journal of Applied Bacteriology*, 79, 322-330.
- HURTADO, A., REGUANT, C., BORDONS, A. & ROZÈS, N. 2011. Expression of *Lactobacillus pentosus* B96 bacteriocin genes under saline stress. *Food Microbiology*, 28, 1339-1344.
- HYRONIMUS, B., LE MARREC, C. & URDACI, M. C. 1998. Coagulin, a bacteriocin-like inhibitory substance produced by *Bacillus coagulans* 14. *Journal of Applied Microbiology*, 85, 42-50.
- INGLIS, R. F., BAYRAMOGLU, B., GILLOR, O. & ACKERMANN, M. 2013. The role of bacteriocins as selfish genetic elements. *Biology Letters*, 9, 20121173.
- JIMENEZ-DIAZ, R., RIOS-SANCHEZ, R. M., DESMAZEAUD, M., RUIZ-BARBA, J. L. & PIARD, J. C. 1993. Plantaricins S and T, Two New Bacteriocins Produced by *Lactobacillus plantarum* LPC010 Isolated from a Green Olive Fermentation. *Applied and Environmental Microbiology*, 59, 1416-24.
- JOERGER, M. C. & KLAENHAMMER, T. R. 1986. Characterization and purification of helveticin J and evidence for a chromosomally determined bacteriocin produced by *Lactobacillus helveticus* 481. *Journal of Bacteriology*, 167, 439-46.
- JOHNSON, B. R., HYMES, J., SANOZKY-DAWES, R., HENRIKSEN, E. D., BARRANGOU, R. & KLAENHAMMER, T. R. 2016. Conserved S-Layer-Associated Proteins Revealed by Exoproteomic Survey of S-Layer-Forming *Lactobacilli*. *Applied and Environmental Microbiology*, 82, 134-45.
- KAISER, A. L. & MONTVILLE, T. J. 1996. Purification of the bacteriocin bavaricin MN and characterization of its mode of action against *Listeria monocytogenes* Scott A cells and lipid vesicles. *Applied and Environmental Microbiology*, 62, 4529-4535.
- KALMOKOFF, M. L., CYR, T. D., HEFFORD, M. A., WHITFORD, M. F. & TEATHER, R. M. 2003. Butyriovibriocin AR10, a new cyclic bacteriocin produced by the ruminal anaerobe *Butyriovibrio fibrisolvens* AR10: characterization of the gene and peptide. *Canadian Journal of Microbiology*, 49, 763-73.
- KANATANI, K., OSHIMURA, M. & SANO, K. 1995. Isolation and characterization of acidocin A and cloning of the bacteriocin gene from *Lactobacillus acidophilus*. *Applied and Environmental Microbiology*, 61, 1061-7.
- KATO, T., MATSUDA, T., OGAWA, E., OGAWA, H., KATO, H., DOI, U. & NAKAMURA, R. 1994. Plantaricin-149, a Bacteriocin Produced by *Lactobacillus-Plantarum* Nric-149. *Journal of Fermentation and Bioengineering*, 77, 277-282.
- KAWAI, Y., ISHII, Y., UEMURA, K., KITAZAWA, H., SAITO, T. & ITOH, T. 2001. *Lactobacillus reuteri* LA6 and *Lactobacillus gasseri* LA39 isolated from faeces of the same human infant produce identical cyclic bacteriocin. *Food Microbiology*, 18, 407-415.
- KAWAI, Y., SAITO, T., KITAZAWA, H. & ITOH, T. 1998. Gassericin A; an uncommon cyclic bacteriocin produced by *Lactobacillus gasseri* LA39 linked at N- and C-terminal ends. *Bioscience, Biotechnology, and Biochemistry*, 62, 2438-2440.
- KAWAI, Y., SAITOH, B., TAKAHASHI, O., KITAZAWA, H., SAITO, T., NAKAJIMA, H. & ITOH, T. 2000. Primary amino acid and DNA sequences of gassericin T, a lactacin F-family bacteriocin produced by *Lactobacillus gasseri* SBT2055. *Bioscience, Biotechnology, and Biochemistry*, 64, 2201-2208.
- KOJIC, M., LOZO, J., JOVICIC, B., STRAHINIC, I., FIRA, D. & TOPISIROVIC, L. 2010. Construction of a new shuttle vector and its use for cloning and expression of two plasmid-encoded bacteriocins from *Lactobacillus paracasei* subsp. *paracasei* BGSJ2-8. *International Journal of Food Microbiology*, 140, 117-24.
- KOSTIC, A. D., HOWITT, M. R. & GARRETT, W. S. 2013. Exploring host-microbiota interactions in animal models and humans. *Genes & Development*, 27, 701-718.

- LARSEN, A. G. & NORRUNG, B. 1993. Inhibition of *Listeria-Monocytogenes* by Bavaricin-a, a Bacteriocin Produced by *Lactobacillus-Bavaricus* Mi401. *Letters in Applied Microbiology*, 17, 132-134.
- LE MARREC, C., HYRONIMUS, B., BRESSOLLIER, P., VERNEUIL, B. & URDACI, M. C. 2000. Biochemical and genetic characterization of coagulin, a new antilisterial bacteriocin in the pediocin family of bacteriocins, produced by *Bacillus coagulans* I(4). *Applied and Environmental Microbiology*, 66, 5213-20.
- LEE, S. W., MITCHELL, D. A., MARKLEY, A. L., HENSLER, M. E., GONZALEZ, D., WOHLRAB, A., DORRESTEIN, P. C., NIZET, V. & DIXON, J. E. 2008. Discovery of a widely distributed toxin biosynthetic gene cluster. *Proceedings of the National Academy of Sciences U S A*, 105, 5879-84.
- LEER, R. J., VAN DER VOSSEN, J. M., VAN GIEZEN, M., VAN NOORT JOHANNES, M. & POWWELS, P. H. 1995. Genetic analysis of acidocin B, a novel bacteriocin produced by *Lactobacillus acidophilus*. *Microbiology*, 141, 1629-1635.
- LEONG, K. H., CHEN, Y. S., LIN, Y. H., PAN, S. F., YU, B., WU, H. C. & YANAGIDA, F. 2013. Weissellicin L, a novel bacteriocin from sian-sianzih-isolated *Weissella hellenica* 4-7. *Journal of Applied Microbiology*, 115, 70-6.
- LETZEL, A.-C., PIDOT, S. J. & HERTWECK, C. 2014. Genome mining for ribosomally synthesized and post-translationally modified peptides (RiPPs) in anaerobic bacteria. *BMC Genomics*, 15, 1.
- LIU, L., HAO, T., XIE, Z., HORSMAN, G. P. & CHEN, Y. 2016. Genome mining unveils widespread natural product biosynthetic capacity in human oral microbe *Streptococcus mutans*. *Scientific Reports*, 6.
- LOZO, J., JOVCIC, B., KOJIC, M., DALGALARRONDO, M., CHOBERT, J. M., HAERTLE, T. & TOPISIROVIC, L. 2007. Molecular characterization of a novel bacteriocin and an unusually large aggregation factor of *Lactobacillus paracasei* subsp. *paracasei* BGSJ2-8, a natural isolate from homemade cheese. *Current Microbiology*, 55, 266-71.
- LU, X., YI, L. H., DANG, J., DANG, Y. & LIU, B. F. 2014. Purification of novel bacteriocin produced by *Lactobacillus coryniformis* MXJ 32 for inhibiting bacterial foodborne pathogens including antibiotic-resistant microorganisms. *Food Control*, 46, 264-271.
- MAJHENIČ, A., VENEMA, K., ALLISON, G., MATIJAŠIĆ, B., ROGELJ, I. & KLAENHAMMER, T. 2004. DNA analysis of the genes encoding acidocin LF221 A and acidocin LF221 B, two bacteriocins produced by *Lactobacillus gasseri* LF221. *Applied Microbiology and Biotechnology*, 63, 705-714.
- MALDONADO-BARRAGAN, A., CABALLERO-GUERRERO, B., LUCENA-PADROS, H. & RUIZ-BARBA, J. L. 2013. Induction of bacteriocin production by coculture is widespread among plantaricin-producing *Lactobacillus plantarum* strains with different regulatory operons. *Food Microbiology*, 33, 40-7.
- MALDONADO-BARRAGAN, A., CABALLERO-GUERRERO, B., MARTIN, V., RUIZ-BARBA, J. L. & RODRIGUEZ, J. M. 2016. Purification and genetic characterization of gassericin E, a novel co-culture inducible bacteriocin from *Lactobacillus gasseri* EV1461 isolated from the vagina of a healthy woman. *BMC Microbiology*, 16, 37.
- MALDONADO, A., RUIZ-BARBA, J. L. & JIMENEZ-DIAZ, R. 2003. Purification and genetic characterization of plantaricin NC8, a novel coculture-inducible two-peptide bacteriocin from *Lactobacillus plantarum* NC8. *Applied and Environmental Microbiology*, 69, 383-9.
- MARSH, A. J., O'SULLIVAN, O., ROSS, R. P., COTTER, P. D. & HILL, C. 2010. In silico analysis highlights the frequency and diversity of type 1 lantibiotic gene clusters in genome sequenced bacteria. *BMC Genomics*, 11, 679.
- MARTINEZ, B., BOTTIGER, T., SCHNEIDER, T., RODRIGUEZ, A., SAHL, H. G. & WIEDEMANN, I. 2008. Specific interaction of the unmodified bacteriocin Lactococcin 972 with the cell wall precursor lipid II. *Applied and Environmental Microbiology*, 74, 4666-70.
- MARTINEZ, B., RODRIGUEZ, A. & SUAREZ, J. E. 2000. Lactococcin 972, a bacteriocin that inhibits septum formation in lactococci. *Microbiology*, 146 (Pt 4), 949-55.

- MASUDA, Y., ONO, H., KITAGAWA, H., ITO, H., MU, F., SAWA, N., ZENDO, T. & SONOMOTO, K. 2011. Identification and characterization of leucocyclicin Q, a novel cyclic bacteriocin produced by *Leuconostoc mesenteroides* TK41401. *Applied and Environmental Microbiology*, 77, 8164-70.
- MATHIESEN, G., HUEHNE, K., KROECKEL, L., AXELSSON, L. & EIJSINK, V. G. 2005. Characterization of a new bacteriocin operon in sakacin P-producing *Lactobacillus sakei*, showing strong translational coupling between the bacteriocin and immunity genes. *Applied and Environmental Microbiology*, 71, 3565-3574.
- MATHUR, H., REA, M. C., COTTER, P. D., HILL, C. & ROSS, R. P. 2015. The sactibiotic subclass of bacteriocins: an update. *Current Protein & Peptide Science*, 16.
- MCAULIFFE, O., ROSS, R. P. & HILL, C. 2001. Lantibiotics: structure, biosynthesis and mode of action. *FEMS Microbiology Reviews*, 25, 285-308.
- MCCLERREN, A. L., COOPER, L. E., QUAN, C., THOMAS, P. M., KELLEHER, N. L. & VAN DER DONK, W. A. 2006. Discovery and in vitro biosynthesis of haloduracin, a two-component lantibiotic. *Proceedings of the National Academy of Sciences of the USA*, 103, 17243-8.
- MESSAOUDI, S., KERGOURLAY, G., DALGALARRONDO, M., CHOISSET, Y., FERCHICHI, M., PREVOST, H., PILET, M. F., CHOBERT, J. M., MANAI, M. & DOUSSET, X. 2012. Purification and characterization of a new bacteriocin active against *Campylobacter* produced by *Lactobacillus salivarius* SMXD51. *Food Microbiology*, 32, 129-34.
- MOLLOY, E. M., COTTER, P. D., HILL, C., MITCHELL, D. A. & ROSS, R. P. 2011. Streptolysin S-like virulence factors: the continuing saga. *Nature Reviews Microbiology*, 9, 670-81.
- MORTVEDT, C. I., NISSEN-MEYER, J., SLETTEN, K. & NES, I. F. 1991. Purification and amino acid sequence of lactocin S, a bacteriocin produced by *Lactobacillus sake* L45. *Applied and Environmental Microbiology*, 57, 1829-34.
- MURPHY, K., O'SULLIVAN, O., REA, M. C., COTTER, P. D., ROSS, R. P. & HILL, C. 2011. Genome mining for radical SAM protein determinants reveals multiple sactibiotic-like gene clusters. *PLoS One*, 6, e20852.
- NISSEN-MEYER, J., LARSEN, A. G., SLETTEN, K., DAESCHEL, M. & NES, I. F. 1993. Purification and characterization of plantaricin A, a *Lactobacillus plantarum* bacteriocin whose activity depends on the action of two peptides. *J Gen Microbiol*, 139, 1973-8.
- NISSEN-MEYER, J., OPPEGARD, C., ROGNE, P., HAUGEN, H. S. & KRISTIANSEN, P. E. 2010. Structure and Mode-of-Action of the Two-Peptide (Class-IIb) Bacteriocins. *Probiotics and Antimicrobial Proteins*, 2, 52-60.
- NODA, M., MIYAUCHI, R., DANSHITSOODOL, N., HIGASHIKAWA, F., KUMAGAI, T., MATOBA, Y. & SUGIYAMA, M. 2015. Characterization and Mutational Analysis of a Two-Polypeptide Bacteriocin Produced by Citrus Iyo-Derived *Lactobacillus brevis* 174A. *Biological and Pharmaceutical Bulletin*, 38, 1902-9.
- O'SHEA, E. F., O'CONNOR, P. M., O'SULLIVAN, O., COTTER, P. D., ROSS, R. P. & HILL, C. 2013. Bactofencin A, a new type of cationic bacteriocin with unusual immunity. *MBio*, 4, e00498-13.
- O'SHEA, E. F., O'CONNOR, P. M., RAFTIS, E. J., O'TOOLE, P. W., STANTON, C., COTTER, P. D., ROSS, R. P. & HILL, C. 2011. Production of multiple bacteriocins from a single locus by gastrointestinal strains of *Lactobacillus salivarius*. *Journal of Bacteriology*, 193, 6973-6982.
- OH, S., ROH, H., KO, H. J., KIM, S., KIM, K. H., LEE, S. E., CHANG, I. S., KIM, S. & CHOI, I. G. 2011. Complete genome sequencing of *Lactobacillus acidophilus* 30SC, isolated from swine intestine. *Journal of Bacteriology*, 193, 2882-3.
- PAPAGIANNI, M. & PAPAMICHAEL, E. M. 2011. Purification, amino acid sequence and characterization of the class IIa bacteriocin weissellin A, produced by *Weissella paramesenteroides* DX. *Bioresource Technology*, 102, 6730-6734.
- PAPATHANASOPOULOS, M. A., KRIER, F., REVOL-JUNELLES, A. M., LEFEBVRE, G., LE CAER, J. P., VON HOLY, A. & HASTINGS, J. W. 1997. Multiple bacteriocin production by *Leuconostoc mesenteroides* TA33a and other *Leuconostoc*/*Weissella* strains. *Current Microbiology*, 35, 331-5.

- PEI, J. J., YUAN, Y. H. & YUE, T. L. 2013. Primary characterization of bacteriocin paracin C - A novel bacteriocin produced by *Lactobacillus paracasei*. *Food Control*, 34, 168-176.
- PETERNEL, M. Z., MAJHENIČ, A. Č., HOLO, H., NES, I. F., SALEHIAN, Z., BERLEC, A. & ROGELJ, I. 2010. Wide-inhibitory spectra bacteriocins produced by *Lactobacillus gasseri* K7. *Probiotics and Antimicrobial Proteins*, 2, 233-240.
- QUADRI, L. E., SAILER, M., ROY, K. L., VEDERAS, J. C. & STILES, M. E. 1994. Chemical and genetic characterization of bacteriocins produced by *Carnobacterium piscicola* LV17B. *The Journal of Biological Chemistry*, 269, 12204-11.
- RAMNATH, M., BEUKES, M., TAMURA, K. & HASTINGS, J. W. 2000. Absence of a putative mannose-specific phosphotransferase system enzyme IIAB component in a leucocin A-resistant strain of *Listeria monocytogenes*, as shown by two-dimensional sodium dodecyl sulfate-polyacrylamide gel electrophoresis. *Appl Environ Microbiol*, 66, 3098-101.
- REA, M. C., SIT, C. S., CLAYTON, E., O'CONNOR, P. M., WHITTAL, R. M., ZHENG, J., VEDERAS, J. C., ROSS, R. P. & HILL, C. 2010. Thuricin CD, a posttranslationally modified bacteriocin with a narrow spectrum of activity against *Clostridium difficile*. *Proceedings of the National Academy of Sciences USA*. United States.
- REMIGER, A., EIJSINK, V., EHRMANN, M., SLETTEN, K., NES, I. & VOGEL, R. 1999. Purification and partial amino acid sequence of plantaricin 1.25 $\alpha\alpha\alpha$ and 1.25 $\beta\beta\beta$, two bacteriocins produced by *Lactobacillus plantarum* TMW1. 25. *Journal of Applied Microbiology*, 86, 1053-1058.
- REVOL-JUNELLES, A. M., MATHIS, R., KRIER, F., FLEURY, Y., DELFOUR, A. & LEEBVRE, G. 1996. *Leuconostoc mesenteroides* subsp. *mesenteroides* FR52 synthesizes two distinct bacteriocins. *Letters in Applied Microbiology*, 23, 120-124.
- RUTHERFORD, K., PARKHILL, J., CROOK, J., HORSNELL, T., RICE, P., RAJANDREAM, M. A. & BARRELL, B. 2000. Artemis: sequence visualization and annotation. *Bioinformatics*, 16, 944-5.
- SAHOO, T. K., JENA, P. K., PATEL, A. K. & SESHADRI, S. 2015. Purification and Molecular Characterization of the Novel Highly Potent Bacteriocin TSU4 Produced by *Lactobacillus animalis* TSU4. *Applied Biochemistry and Biotechnology*, 177, 90-104.
- SANDERS, M. & KLAENHAMMER, T. 2001. Invited review: the scientific basis of *Lactobacillus acidophilus* NCFM functionality as a probiotic. *Journal of Dairy Science*, 84, 319-331.
- SAWA, N., OKAMURA, K., ZENDO, T., HIMENO, K., NAKAYAMA, J. & SONOMOTO, K. 2010. Identification and characterization of novel multiple bacteriocins produced by *Leuconostoc pseudomesenteroides* QU 15. *Journal of Applied Microbiology*, 109, 282-91.
- SIMON, L., FREMAUX, C., CENATIEMPO, Y. & BERJEAUD, J. 2002. Sakacin G, a new type of antilisterial bacteriocin. *Applied and Environmental Microbiology*, 68, 6416-6420.
- SKAUGEN, M., ABILDGAARD, C. I. & NES, I. F. 1997. Organization and expression of a gene cluster involved in the biosynthesis of the lantibiotic lactocin S. *Molecular Genetics and Genomics*, 253, 674-86.
- SOBRINO, O. J., RODRIGUEZ, J. M., MOREIRA, W. L., CINTAS, L. M., FERNANDEZ, M. F., SANZ, B. & HERNANDEZ, P. E. 1992. Sakacin M, a bacteriocin-like substance from *Lactobacillus sake* 148. *International Journal of Food Microbiology*, 16, 215-25.
- SOLIMAN, W., WANG, L., BHATTACHARJEE, S. & KAUR, K. 2011. Structure-activity relationships of an antimicrobial peptide plantaricin s from two-peptide class IIb bacteriocins. *Journal of Medicinal Chemistry*, 54, 2399-408.
- SRIONNUAL, S., YANAGIDA, F., LIN, L.-H., HSIAO, K.-N. & CHEN, Y.-S. 2007. Weissellicin 110, a newly discovered bacteriocin from *Weissella cibaria* 110, isolated from plaasom, a fermented fish product from Thailand. *Applied and Environmental Microbiology*, 73, 2247-2250.
- STEPHENS, S. K., FLORIANO, B., CATHCART, D. P., BAYLEY, S. A., WITT, V. F., JIMÉNEZ-DÍAZ, R., WARNER, P. J. & RUIZ-BARBA, J. L. 1998. Molecular Analysis of the Locus Responsible for Production of Plantaricin S, a Two-Peptide Bacteriocin Produced by *Lactobacillus plantarum* LPC010. *Applied and Environmental Microbiology*, 64, 1871-1877.

- SUDIRMAN, I., MATHIEU, F., MICHEL, M. & LEFEBVRE, G. 1993. Detection and properties of curvaticin 13, a bacteriocin-like substance produced by *Lactobacillus curvatus* SB13. *Current Microbiology*, 27, 35-40.
- SUN, Z., HARRIS, H. M., MCCANN, A., GUO, C., ARGIMON, S., ZHANG, W., YANG, X., JEFFERY, I. B., COONEY, J. C., KAGAWA, T. F., LIU, W., SONG, Y., SALVETTI, E., WROBEL, A., RASINKANGAS, P. & PARKHILL, J. 2015. Expanding the biotechnology potential of lactobacilli through comparative genomics of 213 strains and associated genera. *Nature Communications*, 6, 8322.
- SVETOCH, E. A., ERUSLANOV, B. V., LEVCHUK, V. P., PERELYGIN, V. V., MITSEVICH, E. V., MITSEVICH, I. P., STEPANSHIN, J., DYATLOV, I., SEAL, B. S. & STERN, N. J. 2011. Isolation of *Lactobacillus salivarius* 1077 (NRRL B-50053) and Characterization of Its Bacteriocin, Including the Antimicrobial Activity Spectrum. *Applied and Environmental Microbiology*, 77, 2749-2754.
- TAHARA, T., KANATANI, K., YOSHIDA, K., MIURA, H., SAKAMOTO, M. & OSHIMURA, M. 1992. Purification and Some Properties of Acidocin-8912, a Novel Bacteriocin Produced by *Lactobacillus-Acidophilus* Tk8912. *Bioscience Biotechnology and Biochemistry*, 56, 1212-1215.
- TAHARA, T., OSHIMURA, M., UMEZAWA, C. & KANATANI, K. 1996. Isolation, partial characterization, and mode of action of Acidocin J1132, a two-component bacteriocin produced by *Lactobacillus acidophilus* JCM 1132. *Applied and Environmental Microbiology*, 62, 892-897.
- TEN BRINK, B., MINEKUS, M., VAN DER VOSSEN, J. & LEER, R. 1994. Antimicrobial activity of lactobacilli: preliminary characterization and optimization of production of acidocin B, a novel bacteriocin produced by *Lactobacillus acidophilus* M46. *The Journal of Applied Bacteriology*, 77, 140-148.
- TICHACZEK, P. S., VOGEL, R. F. & HAMMES, W. P. 1993. Cloning and sequencing of curA encoding curvacin A, the bacteriocin produced by *Lactobacillus curvatus* LTH1174. *Archives of Microbiology*, 160, 279-83.
- TICHACZEK, P. S., VOGEL, R. F. & HAMMES, W. P. 1994. Cloning and sequencing of sakP encoding sakacin P, the bacteriocin produced by *Lactobacillus sake* LTH 673. *Microbiology*, 140, 361-367.
- TODOROV, S., ONNO, B., SOROKINE, O., CHOBERT, J. M., IVANOVA, I. & DOUSSET, X. 1999. Detection and characterization of a novel antibacterial substance produced by *Lactobacillus plantarum* ST 31 isolated from sourdough. *International Journal of Food Microbiology*, 48, 167-77.
- TODOROV, S. D., RACHMAN, C., FOURRIER, A., DICKS, L. M., VAN REENEN, C. A., PREVOST, H. & DOUSSET, X. 2011. Characterization of a bacteriocin produced by *Lactobacillus sakei* R1333 isolated from smoked salmon. *Anaerobe*, 17, 23-31.
- TULINI, F. L., LOHANS, C. T., BORDON, K. C., ZHENG, J., ARANTES, E. C., VEDERAS, J. C. & DE MARTINIS, E. C. 2014. Purification and characterization of antimicrobial peptides from fish isolate *Carnobacterium maltaromaticum* C2: Carnobacteriocin X and carnolysins A1 and A2. *International Journal of Food Microbiology*, 173, 81-8.
- TURNER, D. L., BRENNAN, L., MEYER, H. E., LOHAUS, C., SIETHOFF, C., COSTA, H. S., GONZALEZ, B., SANTOS, H. & SUAREZ, J. E. 1999. Solution structure of plantaricin C, a novel lantibiotic. *European Journal of Biochemistry*, 264, 833-9.
- VAN BELKUM, M. J., MARTIN-VISSCHER, L. A. & VEDERAS, J. C. 2011. Structure and genetics of circular bacteriocins. *Trends in Microbiology*, 19, 411-418.
- VAN REENEN, C. A., CHIKINDAS, M. L., VAN ZYL, W. H. & DICKS, L. M. 2003. Characterization and heterologous expression of a class IIa bacteriocin, plantaricin 423 from *Lactobacillus plantarum* 423, in *Saccharomyces cerevisiae*. *International Journal of Food Microbiology*, 81, 29-40.
- VAUGHAN, A., EIJSINK, V., O'SULLIVAN, T., O'HANLON, K. & VAN SINDEREN, D. 2001. An analysis of bacteriocins produced by lactic acid bacteria isolated from malted barley. *Journal of Applied Microbiology*, 91, 131-138.

- VAUGHAN, A., EIJSINK, V. G. & VAN SINDEREN, D. 2003. Functional characterization of a composite bacteriocin locus from malt isolate *Lactobacillus sakei* 5. *Applied and Environmental Microbiology*, 69, 7194-203.
- VENUGOPAL, H., EDWARDS, P. J., SCHWALBE, M., CLARIDGE, J. K., LIBICH, D. S., STEPPER, J., LOO, T., PATCHETT, M. L., NORRIS, G. E. & PASCAL, S. M. 2011. Structural, dynamic, and chemical characterization of a novel S-glycosylated bacteriocin. *Biochemistry*, 50, 2748-55.
- VERA PINGITORE, E., HEBERT, E. M., NADER-MACIAS, M. E. & SESMA, F. 2009. Characterization of salivaricin CRL 1328, a two-peptide bacteriocin produced by *Lactobacillus salivarius* CRL 1328 isolated from the human vagina. *Research in Microbiology*, 160, 401-8.
- VIGNOLO, G., FADDA, S., DE KAIRUZ, M., DE RUIZ HOLGADO, A. P. & OLIVER, G. 1996. Control of *Listeria monocytogenes* in ground beef by 'Lactocin 705', a bacteriocin produced by *Lactobacillus casei* CRL 705. *International Journal of Food Microbiology*, 29, 397-402.
- WALSH, C. J., GUINANE, C. M., HILL, C., ROSS, R. P., O'TOOLE, P. W. & COTTER, P. D. 2015. In silico identification of bacteriocin gene clusters in the gastrointestinal tract, based on the Human Microbiome Project's reference genome database. *BMC Microbiology*, 15, 183.
- WALSH, M. C., GARDINER, G. E., HART, O. M., LAWLOR, P. G., DALY, M., LYNCH, B., RICHERT, B. T., RADCLIFFE, S., GIBLIN, L., HILL, C., FITZGERALD, G. F., STANTON, C. & ROSS, P. 2008. Predominance of a bacteriocin-producing *Lactobacillus salivarius* component of a five-strain probiotic in the porcine ileum and effects on host immune phenotype. *FEMS Microbiology Ecology*, 64, 317-27.
- WANG, H., FEWER, D. P. & SIVONEN, K. 2011. Genome mining demonstrates the widespread occurrence of gene clusters encoding bacteriocins in cyanobacteria. *PloS One*, 6, e22384.
- WEST, C. A. & WARNER, P. J. 1988. Plantacin B, a bacteriocin produced by *Lactobacillus plantarum* NCDO 1193. *FEMS Microbiology Letters*, 49, 163-165.
- WIEDEMANN, I., BOTTIGER, T., BONELLI, R. R., SCHNEIDER, T., SAHL, H. G. & MARTINEZ, B. 2006. Lipid II-based antimicrobial activity of the lantibiotic plantaricin C. *Applied and Environmental Microbiology*, 72, 2809-14.
- XIRAPHI, N., GEORGALAKI, M., DRIESSCHE, G. V., DEVREESE, B., BEEUMEN, J. V., TSAKALIDOU, E., METAXOPOULOS, J. & DROSINOS, E. H. 2006. Purification and characterization of curvaticin L442, a bacteriocin produced by *Lactobacillus curvatus* L442. *Antonie Van Leeuwenhoek*, 89, 19-26.
- YANG, S.-C., LIN, C.-H., SUNG, C. T. & FANG, J.-Y. 2014. Antibacterial activities of bacteriocins: application in foods and pharmaceuticals. *Frontiers in microbiology*, 5, 241.
- ZHANG, H., LIU, L., HAO, Y., ZHONG, S., LIU, H., HAN, T. & XIE, Y. 2013. Isolation and partial characterization of a bacteriocin produced by *Lactobacillus plantarum* BM-1 isolated from a traditionally fermented Chinese meat product. *Microbiology and Immunology*, 57, 746-55.
- ZHAO, S., HAN, J., BIE, X., LU, Z., ZHANG, C. & LV, F. 2016. Purification and Characterization of Plantaricin JLA-9: A Novel Bacteriocin against *Bacillus* spp. Produced by *Lactobacillus plantarum* JLA-9 from Suan-Tsai, a Traditional Chinese Fermented Cabbage. *Journal of Agricultural and Food Chemistry*, 64, 2754-2764.
- ZHAO, X. & KUIPERS, O. P. 2016. Identification and classification of known and putative antimicrobial compounds produced by a wide variety of Bacillales species. *BMC Genomics*, 17, 882.

Chapter 4: Reincarnation of Bacteriocins from the *Lactobacillus* Pangenomic Graveyard

Mass spectrometry and peptide purification was carried out by Ms. Paula O'Connor, vector design and heterologous expression in *Lactobacillus* host was carried out by Dr. Beatriz Mesa Pereira

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Abstract

Bacteria commonly produce narrow spectrum bacteriocins as a means of inhibiting closely related species competing for similar resources in an environment. The increasing availability of genomic data means that it is becoming easier to identify bacteriocins encoded within genomes. Often, however, the presence of bacteriocin genes in a strain does not always translate into biological antimicrobial activity. For example, when analysing the *Lactobacillus* pangenome we identified strains encoding ten pediocin-like bacteriocin structural genes which failed to display inhibitory activity. Nine of these bacteriocins were novel whilst one was identified as the previously characterised bacteriocin ‘penocin A’. The composition of these bacteriocin operons varied between strains, often with key components missing which are required for bacteriocin production, such as dedicated bacteriocin transporters and accessory proteins. In an effort to functionally express these bacteriocins, the structural genes for the ten pediocin homologs were cloned alongside the dedicated pediocin PA-1 transporter in both *Escherichia coli* and *Lactobacillus paracasei* heterologous hosts. Each bacteriocin was cloned with its native leader sequence and as a fusion protein with the pediocin PA-1 leader sequence. Several of these bacteriocins displayed a broader spectrum of inhibition than the original pediocin PA-1. We show how potentially valuable bacteriocins can easily be ‘reincarnated’ from *in silico* data and produced *in vitro* despite often lacking the necessary accompanying machinery. Moreover, the study demonstrates how genomic datasets such as the *Lactobacillus* pangenome harbour a potential “arsenal” of antimicrobial activity with the possibility of being activated when expressed in more genetically amenable hosts.

Introduction

Bacteria exist in complex communities, under constant competition from other strains and species for nutrients and space. The production of antimicrobial peptides known as bacteriocins has been shown to be one means by which such strains can gain a competitive advantage (Kommineni et al., 2015). Bacteriocins can be broad spectrum, inhibiting a variety of bacteria, or narrow spectrum where they inhibit primarily closely related species. As closely related species are more likely to occupy the same environmental niche as the producer, these bacteriocin genes could offer a potentially useful armoury of antimicrobials in helping the producer establish itself in such a niche.

The increasing availability of genomic data has changed the way we identify and study bacteriocins in communities. Bioinformatic screening tools such as BAGEL (de Jong et al., 2010) and antiSMASH (Weber et al., 2015) can now process vast amounts of genomic data to search for antimicrobial operons and genes (Walsh et al., 2015, Letzel et al., 2014). This allows us to identify previously uncharacterised bacteriocins and antibiotics, and to understand the extent of which strains encode these natural weapons for targeting competitors. In many of these cases however, the bacteriocin genes appear to be inactive antimicrobial relics which are unlikely to play an active role given the degradation of the surrounding accessory genes. Mutations within genes, loss of key genes within operons and tight transcriptional regulation can all prevent cells from producing these antimicrobials. This means that many such strains harbour potentially useful bacteriocins that are destined to remain uncharacterised due to a lack of *in vitro* production. One method to overcome this issue is to clone the antimicrobial operon into a host where expression can be controlled. This allows for the natural bacteriocin regulation to be circumvented and/or gene loss to be overcome, thus ensuring production of otherwise unavailable antimicrobials for further characterisation and potential exploitation.

In this study we focused on the expression of potential class IIa bacteriocins from members of the *Lactobacillus* Genus Complex. Bacteriocins are divided into different classes based on their

modifications, structure and mode of action. Class II bacteriocins are not subject to extensive post-translational modification and the class IIa bacteriocins are single peptides with a highly conserved 'YGNGV' N-terminal sequence. These bacteriocins (also known as 'pediocin-like' bacteriocins) are relatively narrow spectrum and display high levels of activity against *Listeria* species (Cotter et al., 2005). They bind to the mannose phosphotransferase transport system in sensitive strains and subsequently induce pore formation which leads to cell death (Zhou et al., 2016). The effective production of these bacteriocins depends on the production of several other associated proteins (Fimland et al., 2005). For example, an associated ABC transporter must be produced by cells in order to transport the bacteriocin outside the cell, and an immunity protein is also required to protect the producing strain from being killed by its own bacteriocin (Dridger et al., 2006). Certain class IIa bacteriocins also require an accessory protein for correct disulphide bond formation (Oppegard et al., 2015). These operons may also have a three-component regulatory system which regulates expression of the bacteriocin. Here, when the concentration of an inducer peptide encoded within the operon reaches a certain level it signals a transmembrane histidine kinase which in turn activates a response regulator which initiates transcription of the bacteriocin operon (Ennahar et al., 2000).

The *Lactobacillus* Genus Complex analysed in this study encompasses the *Lactobacillus*, *Pediococcus*, *Leuconostoc*, *Weissella*, *Fructobacillus* and *Oenococcus* genera and numerous pediocin-like bacteriocins have been associated with this grouping (Collins et al., 2017). Previously Sun *et al.* (Sun et al., 2015) sequenced the genomes of 213 strains belonging to this complex, these were then subject to both *in silico* and *in vitro* bacteriocin screening (Collins et al., 2017). Numerous strains from that study were found to encode bacteriocin operons but did not show *in vitro* bacteriocin production. Several of these strains encoded complete operons for pediocin-like bacteriocins, whilst more had incomplete operons harbouring just structural and immunity genes. Whereas regulatory issues may prevent expression of bacteriocins in strains harbouring complete operons, those without the necessary transporter systems seem unlikely to be produced. It is unclear as to why such

strains encode intact bacteriocin and immunity genes whilst lacking the machinery needed to actually produce and secrete these antimicrobials. One potential explanation for this is that these strains may have maintained the bacteriocin immunity gene under selective pressure from these antimicrobials. The neighbouring bacteriocin encoding gene is small and may have simply been maintained due its proximity to the immunity gene, the much larger transport machinery may then have been lost.

In this study we use an expression systems derived by Mesa Pereira *et al.* (Mesa-Pereira et al., 2017) to reincarnate these bacteriocins, allowing for *in vitro* production. It was found that for production of pediocin PA-1, only the structural gene and the transporter were necessary for bacteriocin production and secretion. As some of our putative novel bacteriocins lacked an associated transporter, the pediocin PA-1 transporter was used in each case. Bacteriocin peptides were detected by mass spectrometry and activity was identified by screening against a range of indicator organisms. The systems used have allowed us to isolate seven novel bacteriocins and represents a unique and rapid way of producing bacteriocins. This method allows us to reincarnate otherwise ineffectual antimicrobial relics identified solely by *in silico* methods.

Results

Identification of ‘Silent’ Pediocin Homologs

Previous work performed by our group analysed bacteriocin production in 213 *Lactobacillus* and related species (Collins et al., 2017). *In silico* screening identified the presence of bacteriocin operons (or remnants of operons) encoded within the genome of a large number of these strains. Strains encoding bacteriocins were then tested for *in vitro* bacteriocin production but several strains failed to display antimicrobial activity (Collins et al., 2017, Sun et al., 2015). This study focused on the class IIa bacteriocins; eight strains were found to encode ten of these pediocin-like bacteriocins but failed to display any antimicrobial production. Of these ten potential bacteriocins identified, nine were novel and one was identified as penocin A, a bacteriocin previously characterised from *P. pentosaceus* ATCC 25745 (Diep et al., 2006) (Table 1) .

Typically at least four genes are commonly required for the production of a class II bacteriocin; a structural gene, a transporter, an immunity gene and a gene encoding an accessory protein (Dridger et al., 2006). The operons for the ten “silent” class IIa bacteriocins differed in their composition, with several lacking the genes for some of the necessary bacteriocin associated components (Figure 1). Each of these nine novel bacteriocins were named based on the species which produced them; e.g. ruminicin produced by *L. ruminus*. Of the operons identified, only those encoding hordeiocin and ruminicin were found to encode all four key components for bacteriocin production. The acidicin operon also appeared to be complete as the structural peptide doesn’t contain any cysteine residues for disulphide bond formation, thus the accessory protein is likely unnecessary. The futcin operon was the only other such operon which encoded an ABC transporter for bacteriocin transport and leader cleavage. The remaining operons were composed of two to three genes encoding just the structural gene and immunity protein, with the agilicin operon also encoding an accessory protein.

Heterologous Cloning

As there was no identifiable bacteriocin production from these eight strains, it was decided to express these novel bacteriocins first in an *E. coli* host. A modified pETcocoTM-2 vector, pMPB1, generated by our group was used for bacteriocin expression (Mesa-Pereira et al., 2017). It was previously found that only the structural gene and the ABC transporter are required to express pediocin PA-1 using this system. As over half of the bacteriocins identified here lack an associated ABC transporter, the pediocin PA-1 transporter PedD was used for the expression of each of these bacteriocins. PedD contains an intrinsic domain for cleavage of the bacteriocin leader sequence, and as these transporters rely on this leader sequence for peptide processing each of these bacteriocins were cloned separately using both their native leader sequence and as a fusion protein containing the pediocin PA-1 leader. Recursive PCR was used to generate the genes for each of these fusion proteins; genes for the natural bacteriocins and the PedD transporter were amplified by PCR (Prodromou and Pearl, 1992). An In-Fusion reaction was then used to assemble and join these PCR products to the enzyme-digested pMPB1 vector. For production in *L. paracasei* NFBC 338, a pNZ44-derived vector was used; in this case the bacteriocin was cloned as a fusion with the pediocin leader along with the PedD transporter. PCR products for these reactions were obtained using positive pMPB1 plasmids as a template. In-Fusion reaction was then used to assemble and join these PCR products to the enzyme-digested pNZ44 vector. The vectors used are shown in Supplementary Table 1.

Production

E.coli TunerTM (DE3) cells transformed with the newly constructed plasmids were grown in LB supplemented with glucose to maintain a low-copy number and bacteriocin expression was induced by co-incubation of the clones with 50µM IPTG for three hours. Wells diffusion assays (WDAs) were used to identify bacteriocin activity from the bacterial supernatants and cell lysates. Bacteriocins were exclusively found in the bacterial supernatant. Antimicrobial activity was lower in cases where

the native leader of the bacteriocin sequence was used; with only four of the nine strains displaying zones of inhibition against a sensitive indicator (pediocin 20336a has an identical leader to pediocin PA-1). For expression in *L. paracasei* NFBC 338, cells were transformed by electroporation with the bacteriocin-containing pNZ44 vectors. Positive transformants were grown overnight and the neutralised cell free supernatant was used to identify bacteriocin production in WDAs.

Of the bacteriocins expressed with the pediocin PA-1 leader sequence in *E. coli*, eight of the ten displayed anti-microbial activity from the cellular supernatant against at least one indicator organism (Table 2). Purification of the bacteriocin peptides from the *E. coli* bacterial supernatant and MALDI-TOF mass spectrometry were used to determine the mass of the active peptides. These masses correlated closely with the predicted mass of the bacteriocin structural peptide, allowing us to identify the bacteriocin produced. This approach confirmed the production of nine of the ten bacteriocins, aquaticin was not identified using these methods, potentially due to low levels of production by the cells (Supplementary Figure 1). The percentage amino acid identity of these bacteriocins in comparison to pediocin ranges from 29.5% to 93.2%. Production levels of bacteriocins were shown to vary between the *E. coli* and *L. paracasei* expression systems. *E. coli* transformants actually displayed greater or equal bacteriocin activity compared to those produced by *L. paracasei* (Table 3). The only exceptions were the original pediocin PA-1 which was used as a control and rennicin B which was produced in very low quantities by the *E. coli* producer where production was only noted after purification of the bacteriocin from the cellular supernatant. Interestingly, *L. paracasei* NFBC 338 failed to produce futcin which was produced by *E. coli*.

Spectrum of Activity

The spectrum of activity was determined using WDAs against 32 indicator strains for bacteriocins produced by the *E. coli* transformants encoding the pediocin leader (Table 2). Despite being of the same class of bacteriocins, these novel antimicrobials display a varying spectrum of activity. Interestingly, pediocin 20336a and hordeiocin inhibited the growth of a larger number of

the indicators tested than pediocin PA-1. Aquaticin and rennicin B failed to display antimicrobial activity in the crude supernatant from the *E. coli* heterologous host, whilst acidicin displayed activity exclusively against *L. mali* DSM 20444 in this assay. Many of these bacteriocins, however, can inhibit a wide range of Gram-positive bacteria including potential pathogens such as *Enterococcus faecalis*. As with most class IIa bacteriocins, these also display potent anti-listerial activity. Interestingly, *L. mali* DSM 20444 appears to also be an extremely sensitive indicator for testing the activity of class IIa bacteriocins here and may prove a safer alternative over the use of *Listeria* strains to test the activity of these bacteriocins.

Bacteriocin Structures

Class IIa bacteriocins tend to have a relatively conserved structure. However, some of these novel bacteriocins display key differences in the typical conserved regions associated with previously characterised class IIa bacteriocins. A three-stranded β -sheet structure can be found at the N-terminus, this is often stabilised by a conserved disulphide bridge formed between two cysteine residues at the N-terminus. Because aquaticin has only a single cysteine residue and acidicin completely lacks cysteine residues, these bacteriocins would be unable to produce the conserved disulphide bond. The C-terminus is less conserved and can be composed of one or two α -helices and an elongated C-terminal tail which can fold back on the α -helix, forming a hairpin-like structure. A C-terminal disulphide bond can stabilise this hairpin structure in certain bacteriocins and pediocin 20336a, rennicin A, rennicin B, hordeiocin, agilicin and ruminicin all have the ability to form this disulphide bond (Fimland et al., 2005).

The N-terminal 'YGNGV/L' region is highly conserved in these peptides, interestingly agilicin is the only such bacteriocin where the valine or leucine residue in this sequence has been replaced by an isoleucine. These peptides also contain a conserved hinge region (VD/NWGXA) which separates the N-terminal β sheet configuration from the C-terminal α helix (Uteng et al., 2003). Acidicin

contains a valine to isoleucine substitution in this motif, a modification only previously seen in lactococcin MMFII (Ferchichi et al., 2001).

Discussion

Due to the growing availability of genomic data and the improvement of software a growing number of novel bacteriocins are being identified (Letzel et al., 2014, Zhao and Kuipers, 2016). There continues however, to be a disconnect between the identification of these genes and the actual production of these bacteriocins *in vitro*. Whilst metagenomic data provides the ability to detect these genes, this is often not correlated to the isolation and characterisation of the producing strain. Thus, whilst bacteriocin genes are being discovered at a much greater rate from metagenomic data, the isolation of these antimicrobials themselves has proved more difficult.

One method to bridge the gap between the discovery of bacteriocin genes and their *in vitro* production is to heterologously express these genes in a new host. This could prove particularly valuable for strains that are non-culturable or that are extremely difficult to grow in the laboratory. Developing and optimising cloning techniques for individual bacteriocins requires time, which can make it a laborious task when working with a large number of potential bacteriocin genes identified in a genomic screen. The methods used by Mesa-Pereira *et al.* (Mesa-Pereira et al., 2017) and in this study provide a rapid mechanism to express non-lantibiotic bacteriocins such as class IIa and class IIb bacteriocins. It has been determined that the presence of the bacteriocin structural gene and the bacteriocin transporter is sufficient to express these bacteriocins using this system (Mesa-Pereira et al., 2017). This provides a quick and easy method to produce such bacteriocins, even if the original operons identified are incomplete. Using this method, it was possible to express novel bacteriocins identified from *in silico* screening of the *Lactobacillus* Genus Complex, despite many of these lacking the obligatory genes required for bacteriocin production by the parent strains. It is unclear as to why such strains encode intact bacteriocin and immunity genes whilst lacking the machinery needed to actually produce and secrete these antimicrobials. One potential explanation for this is that these strains may have maintained the bacteriocin immunity gene under selective pressures and that the

neighbouring small bacteriocin encoding gene may also have been maintained whilst the larger transport machinery was lost.

The bacteriocin expression system used is based on the pediocin PA-1 operon, using the associated transporter PedD to transport the expressed bacteriocin from the cell. Each of the ten bacteriocins described here was cloned in an *E. coli* heterologous host alongside this transporter using both its native leader sequence and as a fusion containing the pediocin PA-1 leader as opposed to its own. Of the ten bacteriocins studied here, nine were novel. The bacteriocins varied from 93.2% to 29.5% amino acid identity to pediocin PA-1. Nine of the ten bacteriocins displayed antimicrobial activity (aquaticin activity was not seen and the peptide was not identified after purification and MALDI-TOF mass spectrometry); the production of these bacteriocins shows the flexibility in the PedD transporter and its ability to secrete several bacteriocins. Production levels of these bacteriocins in an *E. coli* host was greater when they were expressed with the pediocin PA-1 leader sequence rather than their own, this is not surprising given that PedD has evolved to cleave the pediocin PA-1 leader. Four bacteriocins were produced and secreted using their native leader which reflects a degree of redundancy in the specificity of the cleavage domain in the PedD transporter.

The bacteriocins produced displayed a varying spectrum of activity despite all belonging to the class IIa bacteriocins. Pediocin PA-1 is an important commercial additive used in food production in the form of powdered fermentates such as ALTA[®] 2351 (Kerry Bioscience) for the inhibition of *Listeria* species as well as other food spoilage and pathogenic bacteria. The discovery of novel bacteriocins here with a greater inhibitory range indicates that alternative bacteriocins may prove to be more effective additives in food; it also opens up the possibility for extending the use of these bacteriocins for alternative applications such as potential therapeutic uses. Further studies into the effect the structure of these bacteriocins can have on bacteriocin activity may also allow for targeted peptide engineering to improve activity and extend their range of inhibition in the future.

The structure of these bacteriocins can be affected by differences in sequences of these peptides. The N-terminal β -sheet structure of these bacteriocins can be stabilised by the presence of a disulphide bridge, aquaticin and acidicin, however, lack the ability to form such a bond. Sit *et al.* previously found that this disulphide bridge can be removed from class IIa bacteriocins; this reduces but does not eliminate the peptides' inhibitory activity (Sit *et al.*, 2012). This may explain the lower levels of activity seen for aquaticin and acidicin. The hydrophobic/amphiphilic C-terminus of these peptides is less conserved than the N-terminus. It is involved in membrane insertion, resulting in pore formation, and also determines the spectrum of activity of the bacteriocins (Johnsen *et al.*, 2005). The C-terminus is composed of an α -helix followed by a C-terminal tail which forms a hairpin and folds back upon the α -helix. This motif can be stabilised by the presence of a C-terminal disulphide bridge which makes the structure less flexible. Class IIa bacteriocins lacking this second disulphide bridge tend to be more heat sensitive and can undergo unfolding, making them less active at 37°C (Kaur *et al.*, 2004). Acidicin, futcin, aquaticin and penocin A all lack the ability to form this disulphide bridge, which may explain the lower levels of activity seen for these bacteriocins, as the majority of the indicator organisms used here are grown at 37°C. In certain bacteriocins, which lack the ability to form this disulphide bridge, the interaction between tryptophan residues found just after the hinge region and at the C-terminus can stabilise the hairpin fold (Fimland *et al.*, 2002). Penocin A and aquaticin both have terminal tryptophan residues which would compensate for an absent disulphide bond. Futcin has a tryptophan residue at position 33 in the mature peptide; however this is not predicted to be involved in the stabilisation of the hairpin fold; acidicin lacks a stabilising terminal tryptophan residue altogether. This may suggest that such an extended hairpin structure does not form in these bacteriocins. Structural differences between these bacteriocins may not only affect their inhibitory activity but also may affect the ability of the pediocin transporter to secrete these bacteriocins. The bacteriocins which display the greatest divergence from pediocin PA-1 were, however, shown to be secreted here indicating a level of redundancy in the transporter which may extend to the production of other unmodified bacteriocins. This potential extension of

the classes of bacteriocins secreted by this system is supported by the activity of the transporter EnkT from *E. faecium* NKR-5-3 which is involved in the transport of a class IIa bacteriocin, two peptides of a class IIb bacteriocin and also an inducer peptide (Sushida et al., 2018). This emphasises the potential flexibility of these bacteriocin ABC transporters.

The novel bacteriocins described here cluster into different groups upon alignment. Pediocin, pediocin 20336a, rennicin A and rennicin B display between 84-93% homology to each other. Despite being 90.9% identical to pediocin PA-1, rennicin B did not display activity in the crude supernatant from the *E. coli* heterologous host; it did however display equal levels of activity compared to rennicin A when expressed in *L. paracasei* NFBC 338. Two amino acid substitutions in rennicin B may explain this as they occur in important structural regions for the bacteriocin. The Gly29-Ser29 substitution is found in the C-terminal α -helix of the peptide which is involved in membrane insertion. The substitution of a non-polar amino acid for a larger polar one here may affect the formation of the helix and membrane insertion. A Gly36-Ser36 substitution occurs in a double glycine motif which follows the α -helix. This motif may provide the flexibility for the C-terminal tail to fold back upon the helix (Fimland et al., 2002), this flexibility may be lost due to the substitution with a larger serine residue.

Hordeiocin, agilicin, futcin and ruminicin to a lesser extent, also cluster together, displaying between 60-76% amino acid identity. Hordeiocin, agilicin and ruminicin all display a relatively broad spectrum of activity (inhibiting between 18-14 strains), whilst futcin is more narrow spectrum (inhibiting nine strains) which again may be due to a lack of a C-terminal stabilising disulphide bridge. Penocin A, acidicin and aquaticin lack a high degree of similarity to each other and the other bacteriocins produced.

Through analysis of the data from previous *in silico* bacteriocin screens there is the potential to use these cloning systems to a far greater extent to increase the current repertoire of unmodified class II bacteriocins. Whilst this study focuses on the *Lactobacillus* Genus Complex, numerous other

studies have analysed large amounts of genomic data from other sources to identify novel bacteriocins. Zheng *et al.* (Zheng et al., 2015) screened 700 shotgun metagenomic datasets from the Human Microbiome Project for the presence of bacteriocin operons. Of the 4875 putative bacteriocin genes found here, there were 3048 potential class II bacteriocins including 50 class IIa pediocin homologs, all of which represent potential candidates for use in this expression system. Similarly Alvarez-Sieiro *et al.* screened 238 genomes of lactic acid bacteria using BAGEL3, from this they identified 785 putative bacteriocin genes of which 514 encoded potential unmodified bacteriocin genes containing 31 class IIa homologs (Alvarez-Sieiro et al., 2016). Other such *in silico* screening studies have identified 209 further unmodified bacteriocin genes (Walsh et al., 2015, Liu et al., 2016, Azevedo et al., 2015, Kjos et al., 2011). While duplications and false positives are likely to occur in these datasets, even if a small proportion of these genes can be analysed using this expression system it represents a significant extension of the class II bacteriocins.

Thus, whilst *in silico* genomic studies can lead to the identification of bacteriocins, often this research is not carried forward for the characterisation of these antimicrobials. The simple system used here outlines how bacteriocin genes identified through *in silico* screening of the *Lactobacillus* Genus Complex could easily be heterologously expressed. Bacteriocins which otherwise would not have been produced by the original strain due to tight regulation of the operon or loss of necessary genes were able to be produced and studied. Ten class IIa bacteriocins were studied here, nine of which were novel. Nine of these bacteriocins were produced and secreted by the PedD transporter, despite showing less than 30% identity to pediocin PA-1, which reflects the permissiveness of the transporter in secreting these peptides. These novel bacteriocins notably extend the group of class IIa bacteriocins, however these would likely not have been produced and analysed if not for the expression systems used here. This has allowed us to reincarnate these bacteriocin relics, and provides the capacity to identify and produce a vast range of novel bacteriocins identified by other *in silico* screens which may otherwise be destined to remain uncharacterised in their genomic graveyard.

Materials and Methods

Strains and Culture Conditions

Bacterial strains and growth conditions used are displayed in Supplementary Table 2. *E. coli* HST08 StellarTM cells (Takara BIO USA, Inc., Mountain View, CA) were used for normal cloning methods, *E. coli* BL21 TunerTM (DE3) cells (Novagen, EMD Millipore, Billerica, MA) were used for expression of the transformed genes. *E. coli* strains were grown in Luria-Bertani (LB) media containing 50µg/ml of ampicillin for plasmid selection. IPTG (Isopropyl β-D-1-thiogalactopyranoside) (Fisher Scientific, Dublin, Ireland) was added to the growth media to induce gene expression. L-(+)-arabinose and D -(+)-glucose (Sigma Aldrich, Arklow, Ireland) were also added to the media to control plasmid levels in recombinant cells. *L. paracasei* NFBC 338 cells were grown in modified MRS media containing 0.05% cysteine and 10µg/ml chloramphenicol (Sigma Aldrich, Arklow, Ireland).

Molecular Cloning and Gene Expression

Total genomic DNA was extracted from the bacteriocin encoding strains using the GenElute Bacterial Genomic DNA Kit (Sigma Aldrich, Arklow, Ireland). Primers were designed for amplification of the bacteriocins and transporter genes as outlined in the In-Fusion HD cloning protocol (Takara BIO USA, Inc., Mountain View, CA). For amplification of genes containing the bacteriocin along with the native leader sequence, the genes were amplified by PCR from the original genomic DNA of the host strain using CloneAmp Hifi PCR premix (Takara BIO USA, Inc., Mountain View, CA). Recursive PCR was used for the synthesis of fusion genes containing the pediocin PA-1 leader sequence joined to the bacteriocin structural gene (Prodromou and Pearl, 1992). In both cases, the fragment containing the transporter encoded gene (*pedD*) was amplified using pMPB1 pedD Fw1 and pMPB1 pedD Rv1 using *P.acidilactici* LMG 2351 as a DNA template. The oligonucleotides used in this study are listed in Supplementary Table 3. PCR products were purified using the Illustra GFX PCR DNA and Gel Band Purification kit (GE Healthcare, UK), these were then inserted into the linearized *SphI*-*AvrII*

pMPB1 vector using In-Fusion HD cloning Plus. The pMPB1 vector is based on the commercial plasmid pETcocoTM-2 which allows a dual control of expression; at transcriptional level by IPTG induction and for amplification at the DNA replication level by L-arabinose (Sektas and Szybalski, 2002).

The constructions were transformed into StellarTM competent cells and colonies were selected on LB agar plates containing 50µg/ml of ampicillin and 0.2% D-glucose. The transformants were confirmed by colony PCR reactions. L-arabinose was used to increase the plasmid copy number in cells and plasmid DNA was isolated using the NucleoSpin plasmid kit (Macherey-Nagel, Duren, Germany) to be analysed subsequently by double digestion and sequencing. For bacteriocin expression, TunerTM (DE3) *E. coli* cells were transformed with the bacteriocin encoding vectors of interest. The transformants were then grown in LB containing 50µg/ml of ampicillin and 0.2% glucose which maintains the plasmid in a single copy state. Once cells had grown to an OD₆₀₀ of 0.5-0.7, IPTG was added at a concentration of 50 µM to induce expression of the bacteriocin genes.

For expression in *L. paracasei* NFBC 338 the pNZ44 plasmid was used which contains the p44 constitutive promoter. Each bacteriocin was cloned containing the pediocin promoter and the pedD transporter, PCR fragments were amplified from positive StellarTM transformants using the pNZ44 pedA FW and pNZ44 pedD RV oligonucleotides. These were inserted into the linearized *NcoI-HindIII* pNZ44 vector using In-Fusion HD cloning Plus. Constructions were cloned into StellarTM competent cells and confirmed as before. For expression, *L. paracasei* NFBC 338 cells were transformed with the bacteriocin-containing plasmids by electroporation. Transformants were grown overnight in MRS containing 0.05% cysteine and 10µg/ml of chloramphenicol.

Bacteriocin Assays

Bacteriocin activity was determined using WDAs. For TunerTM (DE3) *E. coli* transformants both the cell supernatant and the cell lysates were analysed for antimicrobial activity, whilst only the

supernatants were analysed for *L. paracasei* NFBC 338 cells. Cell supernatants were isolated by centrifugation of the liquid cultures at 4000 RCF for 15 minutes, these supernatants were then filtered using 0.20 µm membrane filters. For cell lysates, cell pellets were resuspended in 5 ml of phosphate-buffered saline (PBS), cells were lysed by sonication using a MSE Soniprep 150 (MSE, London, UK). Lysates were subsequently centrifuged at 4000 RCF for 15 minutes and the resulting supernatants were filtered using 0.20µm membrane filters. For the indicator plates, 50µl of an overnight culture of the indicator strain was added to the appropriate media containing 1% agar. Plates were cooled and 7mm wells were bored in the agar. 50µl of the cell supernatants/lysates being tested were added to each well and plates were refrigerated for 2 hours prior to incubation under the appropriate conditions. WDAs were carried out in triplicate for each bacteriocin.

Bacteriocin Purification and Mass Spectrometry

Purification and analysis was carried out for bacteriocins encoding the pediocin PA-1 leader sequence from TunerTM (DE3) *E. coli* transformants. 85ml of each culture supernatant was applied to 2ml SP sepharose columns (GE Healthcare, UK) pre-equilibrated with 25ml 20mM potassium phosphate buffer 25% acetonitrile, pH 2.5. Columns were washed with 20ml 20mM potassium phosphate buffer 25% acetonitrile, pH 2.5, the bacteriocins analysed eluted from columns with 25ml 20mM potassium phosphate buffer 25% acetonitrile containing 2 M KCl, pH 2.5. Eluents were passed through a 6ml, 500mg Strata-E C18 SPE column pre-equilibrated (Phenomenex, Cheshire, UK) with methanol and water. The column was washed with 6ml 30% ethanol and then 6ml 70% 2-propanol 0.1 TFA (IPA). MALDI TOF colony mass spectroscopy was carried out on the eluents using an An Axima TOF²plus MALDI TOF mass spectrometer (Shimadzu Biotech, Manchester, UK) in positive-ion reflectron mode.

Figures and Tables

Figure 1. Class IIa Bacteriocin Operons

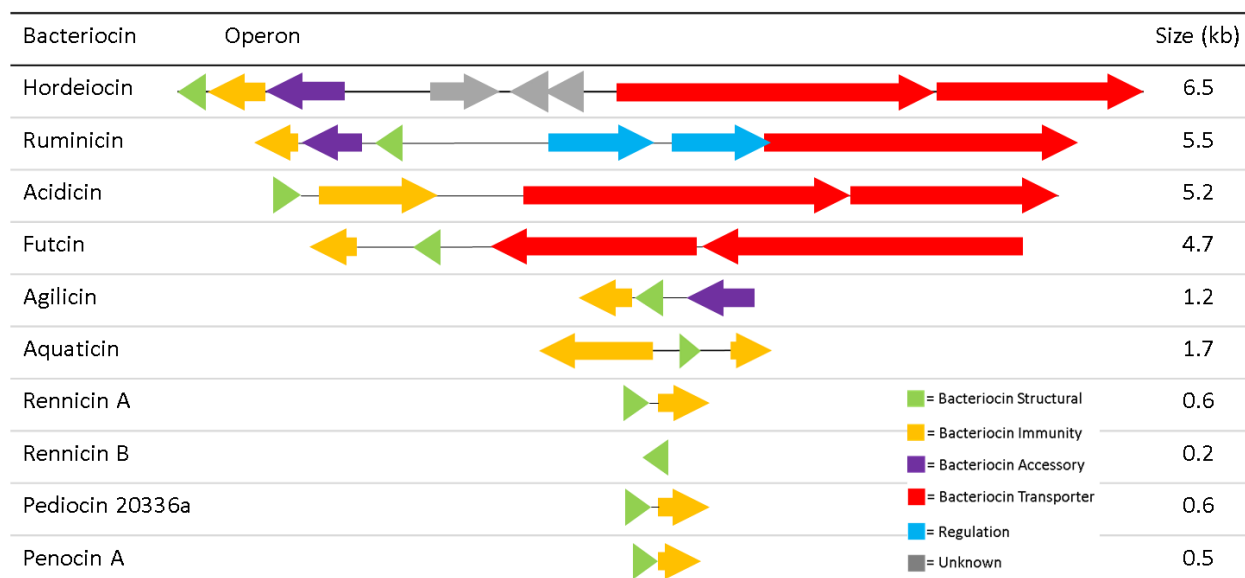


Table 1. Bacteriocins analysed and percentage identity to pediocin PA-1

Encoding Strain	Bacteriocin	Leader	Structural Gene	Structural Gene % Amino Acid Identity to Pediocin PA-1
<i>P. acidilactici</i> LMG 2351	Pediocin PA-1 (Peda)	-----MKRIEKLTEKEMANIIGG -KYYGNGVTCG -KHSCSVDWGRATTCT INNGAMAWATGGHGNHRC----	-	-
<i>P. pentosaceus</i> DSM 20336	Pediocin 20336a (Ped20336)	-----MKRIEKLTEKEMANIIGG -KYYGNGLYCG -KHSCSVDWGRATTCT INNGAMAWATGGHGNHRC----		93.18
<i>L. rennini</i> DSM 20253	Rennin B (RenB)	-----MUSKEELLTQYVNGG -KYYGNGVSCG -KHSCSVDWGRATTCT INNSAMAWATSGHGNHRC----		90.91
<i>L. rennini</i> DSM 20253	Rennin A (RenA)	-----MUSKEELLTQYVNGG -KYYGNGVSCS -KHSCSVDWGRATTCT INNGAMAWATGGHGNHRC----		88.64
<i>L. hordei</i> DSM 19519	Hordeiocin (Hrd)	-----MKKEIEELSEKELVRIIIGG -KYYGNGVSCGCKKHGCKVNWGQAFTCV NRFPANFGH -G-----NC----		56.76
<i>L. agilis</i> DSM 20509	Aglicin (AgI)	MSDK -MENKKKLTADLAKVTCG -SRYYGNGITCG -KHKCTVNWGQAWTCG VNRLANFGH -G-----NC----		56.76
<i>L. ruminis</i> DSM 20403	Ruminin (Rum)	-----MRQLSEKELKKIIMGG -KYYGNGVTCG -KHKCRVDWQAWGCS VNRWGAAGTGKATIGHC----		54.55
<i>L. aquatilis</i> DSM 21051	Aquatich (AqU)	-----MMGG -KNYGNVYCTKKHGYKVDWQAWSII GNNSAANSTTRGAAGWKS-----		47.73
<i>P. pentosaceus</i> DSM 20336	Penocin A (Pena)	-----MT EIKVINDKELKNVVG -KYYGNGVHCG -KKTCTVDWQATASIGKII VNGWTQHGPWAHR-----		47.62
<i>L. futsaii</i> JCM 17355	Futch (Fut)	MKGRYVMKKVI DENSLSLSGG -KYYGNGVSCG -KHTCKVNWGQAWNES VNRWGNSTVNGITGLRQH-----		44.19
<i>L. acidiphilus</i> DSM 15836	Acidich (Acid)	-----LSLESSSYVIGG -KYYGNGLHPKHGKPY INWGQAIQSIGKISYHGWVNGITSGAAGVGRH : ** : **** : : **** :		29.55

Table 2. Spectrum of Bacteriocin Activity

Species	Strain	PedA	Acid	RenB	Hrd	Ped 20336	Aqu	RenA	PenA	Fut	Rum	AgI
<i>Bacillus cereus</i>	DPC 6087											
<i>Enterococcus faecalis</i>	LMG 7397	4.33±0.47			2.67±0.47	4±0		3±0	0.67±0.47	1.67±0.47	1.17±0.24	2.17±0.24
<i>E. faecium</i>	DPC 4898											
<i>E. saccharolyticus</i>	DPC 4902	6±0			3.67±0.47	5.67±0.47		2.33±0.47	1.33±0.94	2±0	2±0	3.33±0.47
<i>E. mundtii</i>	LMG 10748	5±0			2.67±0.47	4.67±0.47		3.33±0.47	1.33±0.94	1.83±0.24	2±0	3±0
<i>Lactobacillus ingluvei</i>	DSM 15946											
<i>L. amylovorus</i>	DSM 20531										0.67	
<i>L. apodemi</i>	DSM 16654	3.33±0.47			2.67±0.47	3.67±0.47		0.67±0.47		0.33±0.47	1.67±0.47	2.67±0.47
<i>L. bulgaricus</i>	LMG 6901											
<i>L. crustorum</i>	JCM 15951	0.33±0.47			1±0	1±0					0.33±0.47	0.33±0.47
<i>L. delbrueckii indicus</i>	DSM 15996											
<i>L. delbrueckii lactis</i>	LMG 7942											
<i>L. farraginis</i>	DSM 18382											
<i>L. amylophilus</i>	DSM 20509				2.50±0.41	0.33±0.47			0.67±0.47		1.33±0.47	
<i>L. intestinalis</i>	DSM 6629											
<i>L. kimchicus</i>	JCM 15530				3±0	0.33±0.47						
<i>L. mali</i>	DSM 20444	7.67±0.47	1.50±0.41		4.33±0.47	6.33±0.47		1±0	1.50±1.08	2.17±0.85	2±0	4.50±0.41
<i>L. nodensis</i>	DSM 16982				3.67±0.47	1.67±0.47						3.50±0.71
<i>L. paralimentarius</i>	DSM 13961	0.67±0.47			1±0.47	1±0.47						
<i>L. plantarum</i>	DSM 13273	0.33±0.47			1.33±0.47	1.33±0.47						0.33±0.47
<i>L. salivarius</i>	DPC 6502											
<i>Leuconostoc fallax</i>	DSM 20189											
<i>Listeria innocua</i>	DPC 3572	8±0			4.67±0.47	7.33±0.47		6.33±0.94	2.50±0.41	2.00±0	3.33±0.47	5±0
<i>Li. monocytogenes</i>	DPC 6893	3±0			2±0	2.67±0.47		2±0	0.67±0.47		1±0	2±0
<i>Li. monocytogenes</i>	DPC 6894	5±0			4±0	4.33±0.47		2±1.41	0.67±0.47	0.83±0.24	2±0	4±0
<i>Li. monocytogenes</i>	WSL 1416	3.33±0.94			2±0.82	3.33±0.94		2.67±0.47	0.67±0.47	1±0	1±0	2±0.82
<i>Pseudomonas aeruginosa</i>	APC 2064											
<i>Pediococcus stilesii</i>	DSM 18001	1±0			1±0	1±0			0.67±0.47			
<i>P. ethanolidurans</i>	DSM 22301	5.67±0.47			3.67±0.47	5.67±0.47		1.50±0.41	2±1.41	3±0	2.17±0.24	3.33±0.47
<i>P. clausenii</i>	DSM 14800				2±0	0.67±0.47			1±0.82		1±0	0.67±0.47
<i>Staphylococcus aureus</i>	C55											
<i>Salmonella typhimurium</i>	LT2											
Total No. of Strains Inhibited		14	1	0	18	18	0	10	12	9	14	14

Antimicrobial activity is calculated as the radius of the zone of inhibition from a well diffusion assay measured in millimetres. PedA, pediocin PA-1. Acid, acidacin. RenB, rennicin B. Hrd, hordeiocin. Ped 20336, pediocin 20336a. Aqu, aquaticin. RenA, rennicin A. PenA, penocin A. Fut, futcin. Rum, ruminicin. AgI, agilicin.

Table 3. Bacteriocin Activity (BU/ml) vs *L. innocua* DPC3572

	<i>E. coli</i> Tuner (DE3)	<i>L. paracasei</i> NFBC338
PedA	+	++
RenA	+	+
Rum	+++	+++
Agl	++	++
Aqu	-	-
RenB	-	+
Acd	-	-
Ped 20336	+	+
Fut	+	-
Hrd	+++	++
PenA	++	+

Bacteriocin units per ml (BU/ml) were calculated as the inverse of the highest dilution of bacterial supernatant showing activity against *L. innocua* DPC3572 in a well diffusion assay. + = 0 – 160 BU/ml, ++ = 320 – 2560 BU/ml, +++ = 5120 – 10240 BU/ml

Supplementary Table 1. Vectors Used

Plasmid	Characteristics
pETcoco TM	Plasmid with T7/ <i>lac</i> promoter for gene expression and araC-P _{BAD} promoter for amplification. Ap ^r .
APC2313	pMPB1, pETcoco TM -2 with modified MCS. Ap ^r .
APC2666	pMPB1, <i>pedApedD</i> . Ap ^r .
APC3139	pMPB1, <i>ped20336pedD</i> . Ap ^r .
APC3140	pMPB1, <i>renApedD</i> . Ap ^r .
APC3141	pMPB1, <i>PLrenApedD</i> . Ap ^r .
APC3142	pMPB1, <i>renBpedD</i> . Ap ^r .
APC3143	pMPB1, <i>PLrenBpedD</i> . Ap ^r .
APC3144	pMPB1, <i>hrdApedD</i> . Ap ^r .
APC3145	pMPB1, <i>PLhrdApedD</i> . Ap ^r .
APC3146	pMPB1, <i>aglApedD</i> . Ap ^r .
APC3147	pMPB1, <i>PLaglApedD</i> . Ap ^r .
APC3148	pMPB1, <i>rumApedD</i> . Ap ^r .
APC3149	pMPB1, <i>PLrumApedD</i> . Ap ^r .
APC3150	pMPB1, <i>aquApedD</i> . Ap ^r .
APC3151	pMPB1, <i>PLaquApedD</i> . Ap ^r .
APC3152	pMPB1, <i>penApedD</i> . Ap ^r .
APC3153	pMPB1, <i>PLpenApedD</i> . Ap ^r .
APC3154	pMPB1, <i>futApedD</i> . Ap ^r .
APC3155	pMPB1, <i>PLfutApedD</i> . Ap ^r .
APC3156	pMPB1, <i>acdApedD</i> . Ap ^r .
APC3157	pMPB1, <i>PLacdApedD</i> . Ap ^r .
APC3489	pNZ44, MCS, Cl ^r
APC3490	pNZ44, <i>pedApedD</i> . Cl ^r .
APC2328	pNZ44, <i>ped20336pedD</i> . Cl ^r .
APC2622	pNZ44, <i>PLrenApedD</i> . Cl ^r .
APC2623	pNZ44, <i>PLrenBpedD</i> . Cl ^r .
APC2763	pNZ44, <i>PLhrdApedD</i> . Cl ^r .
APC2764	pNZ44, <i>PLaglApedD</i> . Cl ^r .
APC3349	pNZ44, <i>PLrumApedD</i> . Cl ^r .
APC3639	pNZ44, <i>PLaquApedD</i> . Cl ^r .
APC3488	pNZ44, <i>PLpenApedD</i> . Cl ^r .
APC3640	pNZ44, <i>PLfutApedD</i> . Cl ^r .
APC3641	pNZ44, <i>PLacdApedD</i> . Cl ^r .

*MCS, multiple cloning site. Ap^r, ampicillin resistant. Cl^r, chloramphenicol resistance. *PL*, pediocin

PA-1 leader sequence fusion gene.

Supplementary Table 2. Bacterial Strains and Growth Conditions

Species	Strain	Growth Media	Temp. (°C)	Conditions
<u>Bacteriocin Encoding Strains</u>				
<i>Lactobacillus acidipiscis</i>	DSM 15836	MRS	30	Anaerobic
<i>L. agilis</i>	DSM 20509	MRS	37	Anaerobic
<i>L. aquaticus</i>	DSM 21051	MRS	37	Anaerobic
<i>L. futsaii</i>	JCM 17355	MRS	30	Aerobic
<i>L. hordei</i>	DSM 19519	MRS	30	Anaerobic
<i>L. rennini</i>	DSM 20253	AAM	30	Aerobic
<i>L. ruminis</i>	DSM 20403	MRS	37	Anaerobic
<i>Pediococcus acidilactici</i>	LMG 2351	MRS	30	Aerobic
<i>P. pentosaceus</i>	DSM 20336	MRS	30	Aerobic
<u>Host Strains</u>				
<i>Escherichia coli</i>	HST08 Stellar TM	LB	37	Aerobic
<i>E. coli</i>	BL21 Turner TM (DE3)	LB	37	Aerobic
<i>L. paracasei</i>	NCC 338	mMRS	37	Anaerobic
<u>Indicator Strains</u>				
<i>Bacillus cereus</i>	DPC 6087	BHI	37	Aerobic
<i>Enterococcus faecalis</i>	LMG 7397	MRS	37	Anaerobic
<i>E. faecium</i>	DPC 4898	MRS	37	Anaerobic
<i>E. saccharolyticus</i>	DPC 4902	MRS	37	Anaerobic
<i>E. mundtii</i>	LMG 10748	MRS	37	Anaerobic
<i>L. amylophilus</i>	DSM 20509	MRS	30	Aerobic
<i>L. amylovorus</i>	DSM 20531	MRS	37	Anaerobic
<i>L. apodemi</i>	DSM 16654	MRS	37	Anaerobic
<i>L. bulgaricus</i>	LMG 6901	MRS	37	Anaerobic
<i>L. crustorum</i>	JCM 15951	MRS	30	Aerobic
<i>L. delbrueckii indicus</i>	DSM 15996	MRS	37	Anaerobic
<i>L. delbrueckii lactis</i>	LMG 7942	MRS	37	Anaerobic
<i>L. farraginis</i>	DSM 18382	MRS	30	Anaerobic
<i>L. ingluvei</i>	DSM 15946	MRS	37	Anaerobic
<i>L. intestinalis</i>	DSM 6629	MRS	37	Aerobic
<i>L. kimchicus</i>	JCM 15530	MRS	37	Aerobic
<i>L. mali</i>	DSM 20444	MRS	30	Aerobic
<i>L. nodensis</i>	DSM 16982	MRS	30	Anaerobic
<i>L. paralimentarius</i>	DSM 13961	MRS	30	Anaerobic
<i>L. plantarum</i>	DSM 13273	MRS	37	Aerobic
<i>L. salivarius</i>	DPC 6502	MRS	37	Anaerobic
<i>Leuconostoc fallax</i>	DSM 20189	MRS	30	Aerobic
<i>Listeria innocua</i>	DPC 3572	BHI	37	Aerobic
<i>Li. monocytogenes</i>	DPC 6893	BHI	37	Aerobic
<i>Li. monocytogenes</i>	DPC 6894	BHI	37	Aerobic
<i>Li. monocytogenes</i>	WSL 1416	BHI	37	Aerobic
<i>Pseudomonas aeruginosa</i>	APC 2064	BHI	37	Aerobic
<i>Pediococcus ethanolidurans</i>	DSM 22301	MRS	37	Anaerobic
<i>P. stilesii</i>	DSM 18001	MRS	30	Anaerobic
<i>P. clausenii</i>	DSM 14800	MRS	30	Aerobic
<i>Staphylococcus aureus</i>	C55	BHI	37	Aerobic
<i>Salmonella typhimurium</i>	LT2	BHI	37	Aerobic

Supplementary Table 3. Primers Used

Primer Name	Sequence
pMPB1 pedA Fw1	AGAAGGAGATATAAGCATGAAAAAATTGAAAAATTAAGT
pedApedD Rv1	CAAAACCATATTAACCAGGTGATTATTGATGCCAGCTCAG
pMPB1 renA Fw1	AGAAGGAGATATAAGCATGTTAAGTAAAGAAGAGCTAAC
renApedD Rv1	CAAAACCATATTAACCAGGTGATTAGCATTTATGATTTC
pMPB1 penA Fw1	AGAAGGAGATATAAGCATGACTGAAATTAAGTACTAAACG
penApedD Rv1	CAAAACCATATTAACCAGGTGATTATCTATGTGCCAAGGCCCG
pMPB1 hrdAFw1	AGAAGGAGATATAAGCATGAAGAAAGAAATAGAATTGTGAG
hrdApedD Rv1	CAAAACCATATTAACCAGGTGATTAAACAATTACCATGGCCAAAATTTG
pMPB1 acdA Fw1	AGAAGGAGATATAAGCCTATCTTTAGAAGAGTCTAGTAG
acdApedD Rv1	CAAAACCATATTAACCAGGTGATTAAATGTCGGCCTACTCCAGCAG
pMPB1 futA Fw1	AGAAGGAGATATAAGCATGAAAGGGAGATATGTCAATATG
futApedD Rv1	CAAAACCATATTAACCAGGTGATTAAATGTTGGCGTAATCCTGTTAATC
pMPB1 aglA Fw1	AGAAGGAGATATAAGCATGAGTGATAAATGGAAAAACAAG
aglApedD Rv1	CAAAACCATATTAACCAGGTGATTAGCAGTTACCATGACCAAAGTTG
pMPB1 aquA Fw1	AGAAGGAGATATAAGCATGAATGGAGGAAAAAATTATGG
aquApedD Rv1	CAAAACCATATTAACCAGGTGATTACTTGCTTTTCCATCCTGCGAG
pMPB1 rumA Fw1	AGAAGGAGATATAAGCATGAGACAACCTTTCCGAAAAAG
rumApedD Rv1	CAAAACCATATTAACCAGGTGATTAGCAATGGCCGATTGTAGCC
pMPB1 pedD Fw1	TCACCTGGTTAATATGGTTTTGTAACCAATGTAAAAGG
pMPB1 pedD Rv1	GCTCGAGTGCAGCCTAGGCTATTCTTGATTATGAATTAACC
pNZ44 pedA Fw1	GGAGGCGCTTCCATGAAAAAATTGAAAAATTAAGT
pNZ44 pedD Rv1	GGTTCAAAGAAAGCTCTATTCTTGATTATGAATTAACC
Recursive Primers	
pMPB1 PedL Fw1	AGAAGGAGATATAAGCATGAAAAAATTGAAAAATTAAGTAAAAAGAAATGGCCAATATCATTGGTGG
PLrenA Rv2	CAACCGAGCAAGAATGCTTACTACACGAAACACCATTGCCATAATTTTACCACCAATGATATTGGCC
PLrenA Fw3	GCATTCTTGCTCGGTTGACTGGGGTAAAGCTTTGACTGTACCATTAATAATGGTGCAATGGCTTGG
PLrenApedD Rv4	CCATATTAACCAGGTGATTAGCATTTATGATTTCCTTGGTGACCACCTGTGGTCCAAGCCATTGCCACAT
PLpenA Rv2	CCACATAGCAAGTCTTTTACCACAATGCACTCCGTTACCGTAATACTTACCACCAATGATATTGGCC
PLpenA Fw3	AAAAGACTTGCTATGTGGACTGGGGACAAGCTACAGCTAGCATTGGAAAAATTATAGTGAACGGATGG
PLpenApedD Rv4	CCATATTAACCAGGTGATTATCTATGTGCCAAGGCCCGTGTGTGTCCATCCGTTCACTATAAT
PLhrdA Rv2	CCATGTTTCTTTGTACAGCTAACTCCATTTCCATAGTATTTCCACCAATGATATTGGCC
PLhrdA Fw3	CTGTACAAAGAAACATGGTTGCAAAGTAAATGGGGACAAGCTTTCACTTGCAGCGTTAATCGT
PLhrdApedD Rv4	CCATATTAACCAGGTGATTAAACAATTACCATGGCCAAAATTTGCAAAACGATTAAACGCTGCAAGT
PLacdA Rv2	CCCCAATTAATATATGGTTTTCCATGTTTAGGAATATGAAGACCATTACCATAGTATTTGCCACCAATGATATTGGCC
PLacdA Fw3	ACCATATATTAATTGGGGACAAGCTATACAATCAATAGGCAAAATTTCCATACCATGGTTGGGTTAATGGT
PLacdApedD Rv4	CCATATTAACCAGGTGATTAAATGTCGGCCTACTCCAGCAGCGCCACTAGTTATACCATTAACCCAACCATG
PLfutA Rv2	CCAGTTTACTTTACATGTATGTTTTCCACAAGAACTCCGTTACCGTAGTACTTACCACCAATGATATTGGCC
PLfutA Fw3	ACATGTAAAGTAACTGGGGACAAGCCTGGAACGAAAGTGTTAATCGTTGGGGTAATTCATGGGT
PLfutApedD Rv4	CCATATTAACCAGGTGATTAAATGTTGGCGTAATCCTGTTAATCCATTTACCCATGAATTACCCCAA
PLaglA Rv2	CTTATGTTTGGCACAAGTAATACCGTTACCATAATATCTACTTCCACCAATGATATTGGCC
PLaglA Fw3	ACTTGTGGCAAACATAAGTGCACAGTTAACTGGGGGCAAGCTTGGACTTGCAGGATTAAC
PLaglApedD Rv4	CCATATTAACCAGGTGATTAGCAGTTACCATGACCAAAGTTGGCAAGGCGGTTAACTCCGCAAGTCCA
PLaquA Rv2	CTACTTTATAACCATGCTTTTTTGTACAGTAGACTCCATTTCCATAATTTTTCCACCAATGATATTGGCC
PLaquA Fw3	GCATGGTTATAAAGTAGACTGGGGACAGGCTTGGTCAATTATTGGGAACAATTCCGCAGCGAATTCCG
PLaquApedD Rv4	CCATATTAACCAGGTGATTACTTGCTTTTCCATCCTGCAGCTCCACGAGTTGTCGAATTGCTGCCGAATT
PLrumA Rv2	CACGCGGCACTTGTGCTTGCCGCGAGTAAACGCCGTTTCCATAATACTTGCCACCAATGATATTGGCC
PLrumA Fw3	AAGCACAAGTGCCGCGTGGACTGGGGACAGGCATGGGGATGCAGTGTCACAGATGGGGCGCCGAGTA
PLrumApedD Rv4	CCATATTAACCAGGTGATTAGCAATGGCCGATTGTAGCCTTGCCGCCGTTCTACTGCGCGCCCCATCT

References

- ALVAREZ-SIEIRO, P., MONTALBAN-LOPEZ, M., MU, D. & KUIPERS, O. P. 2016. Bacteriocins of lactic acid bacteria: extending the family. *Appl Microbiol Biotechnol*, 100.
- AZEVEDO, A. C., BENTO, C. B., RUIZ, J. C., QUEIROZ, M. V. & MANTOVANI, H. C. 2015. Distribution and genetic diversity of bacteriocin gene clusters in rumen microbial genomes. *Appl Environ Microbiol*, 81.
- COLLINS, F. W., O'CONNOR, P. M., O'SULLIVAN, O., GÓMEZ-SALA, B., REA, M. C., HILL, C. & ROSS, R. P. 2017. Bacteriocin Gene-Trait matching across the complete *Lactobacillus* Pan-genome. *Scientific reports*, 7, 3481.
- COTTER, P. D., HILL, C. & ROSS, R. P. 2005. Bacteriocins: developing innate immunity for food. *Nature Reviews Microbiology*, 3, 777-88.
- DE JONG, A., VAN HEEL, A. J., KOK, J. & KUIPERS, O. P. 2010. BAGEL2: mining for bacteriocins in genomic data. *Nucleic Acids Research*, 38, W647-51.
- DIEP, D. B., GODAGER, L., BREDE, D. & NES, I. F. 2006. Data mining and characterization of a novel pediocin-like bacteriocin system from the genome of *Pediococcus pentosaceus* ATCC 25745. *Microbiology*, 152, 1649-1659.
- DRIDER, D., FIMLAND, G., HÉCHARD, Y., MCMULLEN, L. M. & PRÉVOST, H. 2006. The Continuing Story of Class IIa Bacteriocins. *Microbiology and Molecular Biology Reviews*, 70, 564-582.
- ENNAHAR, S., SASHIHARA, T., SONOMOTO, K. & ISHIZAKI, A. 2000. Class IIa bacteriocins: biosynthesis, structure and activity. *FEMS Microbiol Rev*, 24, 85-106.
- FERCHICHI, M., FRERE, J., MABROUK, K. & MANAI, M. 2001. Lactococcin MMFII, a novel class IIa bacteriocin produced by *Lactococcus lactis* MMFII, isolated from a Tunisian dairy product. *FEMS Microbiol Lett*, 205, 49-55.
- FIMLAND, G., EIJSINK, V. G. & NISSEN-MEYER, J. 2002. Mutational analysis of the role of tryptophan residues in an antimicrobial peptide. *Biochemistry*, 41, 9508-15.
- FIMLAND, G., JOHNSEN, L., DALHUS, B. & NISSEN-MEYER, J. 2005. Pediocin-like antimicrobial peptides (class IIa bacteriocins) and their immunity proteins: biosynthesis, structure, and mode of action. *Journal of Peptide Science*, 11, 688-96.
- JOHNSEN, L., FIMLAND, G. & NISSEN-MEYER, J. 2005. The C-terminal domain of pediocin-like antimicrobial peptides (class IIa bacteriocins) is involved in specific recognition of the C-terminal part of cognate immunity proteins and in determining the antimicrobial spectrum. *J Biol Chem*, 280, 9243-50.
- KAUR, K., ANDREW, L. C., WISHART, D. S. & VEDERAS, J. C. 2004. Dynamic relationships among type IIa bacteriocins: temperature effects on antimicrobial activity and on structure of the C-terminal amphipathic alpha helix as a receptor-binding region. *Biochemistry*, 43, 9009-20.
- KJOS, M., BORRERO, J., OPSATA, M., BIRRI, D. J., HOLO, H. & CINTAS, L. M. 2011. Target recognition, resistance, immunity and genome mining of class II bacteriocins from Gram-positive bacteria. *Microbiology*, 157.
- KOMMINENI, S., BRETLE, D. J., LAM, V., CHAKRABORTY, R., HAYWARD, M., SIMPSON, P., CAO, Y., BOUSOUNIS, P., KRISTICH, C. J. & SALZMAN, N. H. 2015. Bacteriocin production augments niche competition by enterococci in the mammalian gastrointestinal tract. *Nature*.
- LETZEL, A.-C., PIDOT, S. J. & HERTWECK, C. 2014. Genome mining for ribosomally synthesized and post-translationally modified peptides (RiPPs) in anaerobic bacteria. *BMC Genomics*, 15, 1.
- LIU, L., HAO, T., XIE, Z., HORSMAN, G. P. & CHEN, Y. 2016. Genome mining unveils widespread natural product biosynthetic capacity in human oral microbe *Streptococcus mutans*. *Scientific Reports*, 6.
- MESA-PEREIRA, B., O'CONNOR, P. M., REA, M. C., COTTER, P. D., HILL, C. & ROSS, R. P. 2017. Controlled functional expression of the bacteriocins pediocin PA-1 and bactofencin A in *Escherichia coli*. *Scientific Reports*, 7.

- OPPEGARD, C., FIMLAND, G., ANONSEN, J. H. & NISSEN-MEYER, J. 2015. The Pediocin PA-1 Accessory Protein Ensures Correct Disulfide Bond Formation in the Antimicrobial Peptide Pediocin PA-1. *Biochemistry*, 54, 2967-74.
- PRODROMOU, C. & PEARL, L. H. 1992. Recursive PCR: a novel technique for total gene synthesis. *Protein Engineering Design and Selection*, 5, 827-829.
- SEKTAS, M. & SZYBALSKI, W. 2002. Novel single-copy pETcoco vector with dual controls for amplification and expression. *InNovations*, 14, 6-8.
- SIT, C. S., LOHANS, C. T., VAN BELKUM, M. J., CAMPBELL, C. D., MISKOLZIE, M. & VEDERAS, J. C. 2012. Substitution of a conserved disulfide in the type IIa bacteriocin, leucocin A, with L-leucine and L-serine residues: effects on activity and three-dimensional structure. *Chembiochem*, 13, 35-8.
- SUN, Z., HARRIS, H. M., MCCANN, A., GUO, C., ARGIMON, S., ZHANG, W., YANG, X., JEFFERY, I. B., COONEY, J. C., KAGAWA, T. F., LIU, W., SONG, Y., SALVETTI, E., WROBEL, A., RASINKANGAS, P. & PARKHILL, J. 2015. Expanding the biotechnology potential of lactobacilli through comparative genomics of 213 strains and associated genera. *Nature Communications*, 6, 8322.
- SUSHIDA, H., ISHIBASHI, N., ZENDO, T., WILAI PUN, P., LEELAWATCHARAMAS, V., NAKAYAMA, J. & SONOMOTO, K. 2018. Evaluation of leader peptides that affect the secretory ability of a multiple bacteriocin transporter, EnkT. *Journal of bioscience and bioengineering*.
- UTENG, M., HAUGE, H. H., MARKWICK, P. R., FIMLAND, G., MANTZILAS, D., NISSEN-MEYER, J. & MUHLE-GOLL, C. 2003. Three-dimensional structure in lipid micelles of the pediocin-like antimicrobial peptide sakacin P and a sakacin P variant that is structurally stabilized by an inserted C-terminal disulfide bridge. *Biochemistry*, 42, 11417-11426.
- WALSH, C. J., GUINANE, C. M., HILL, C., ROSS, R. P., O'TOOLE, P. W. & COTTER, P. D. 2015. In silico identification of bacteriocin gene clusters in the gastrointestinal tract, based on the Human Microbiome Project's reference genome database. *BMC Microbiology*, 15, 183.
- WEBER, T., BLIN, K., DUDELA, S., KRUG, D., KIM, H. U., BRUCCOLERI, R., LEE, S. Y., FISCHBACH, M. A., MULLER, R., WOHLLEBEN, W., BREITLING, R., TAKANO, E. & MEDEMA, M. H. 2015. antiSMASH 3.0-a comprehensive resource for the genome mining of biosynthetic gene clusters. *Nucleic Acids Res*, 43, W237-43.
- ZHAO, X. & KUIPERS, O. P. 2016. Identification and classification of known and putative antimicrobial compounds produced by a wide variety of Bacillales species. *BMC Genomics*, 17, 882.
- ZHENG, J., GÄNZLE, M. G., LIN, X. B., RUAN, L. & SUN, M. 2015. Diversity and dynamics of bacteriocins from human microbiome. *Environmental microbiology*.
- ZHOU, W., WANG, G., WANG, C., REN, F. & HAO, Y. 2016. Both IIC and IID Components of Mannose Phosphotransferase System Are Involved in the Specific Recognition between Immunity Protein PedB and Bacteriocin-Receptor Complex. *PLoS One*, 11, e0164973.



Collins, F. W. J. 2019. An investigation into antimicrobial production in the *Lactobacillus* genus and the fish microbiome. PhD Thesis, University College Cork.

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Chapter 6: General Discussion

As the spread of antibiotic resistance continues, the risks associated with microbial infections are becoming of much greater concern. The need for new therapies for the prevention and treatment of such infections is clear, but the development of novel antimicrobials and new pipelines has dwindled (Burki, 2017). Bacteriocins are one class of antimicrobials which have been generally overlooked when it comes to tackling the issue of antibiotic resistance. These antimicrobial peptides can exhibit potent inhibitory activity, often against clinically important pathogens even at nanomolar concentrations (Cotter et al., 2013). A narrow spectrum of antimicrobial activity for some bacteriocins allows them to target specific pathogens with minimal collateral damage to the host microbiome (Rea et al., 2011). The *in situ* production of bacteriocins by probiotic bacteria or members of the host microbiome also forms the basis for treatment and prevention of intestinal infections (Corr et al., 2007).

Whilst the use of alternative antimicrobials such as bacteriocins and organic acids remains negligible in medicine, the use of cultures which produce these antimicrobials for the safe preservation of foods has been established for millennia (Ross et al., 2002). In particular, the lactic acid bacteria (LAB) have a long association with food preservation, having important functional and protective roles in the production of fermented foods such as yoghurt, cheese, sauerkraut and kimchi. These LAB have been shown to produce a range of metabolites which can lead to the inhibition of potential spoilage microbes. Organic acids are a by-product of LAB metabolism which lowers the pH of the food source, thus inhibiting the growth of spoilage microbes while also modulating the flavour of the food (Rhee et al., 2011). Bacteriocins offer a much more targeted approach for enhancing food safety. Bacteriocins can be introduced into fermented foods either by *in situ* production by starter cultures, or else by the exogenous addition of crude fermentates or purified bacteriocins (Cotter et al., 2005). Nisin, for example, was awarded generally regarded as safe (GRAS) status by the FDA in 1988, and the safe commercial use for decades of this lantibiotic as a food preservative demonstrates the potential of such antimicrobials for wide-scale use in industry (Younes et al., 2017).

In this study we utilised a variety of mechanisms for the identification and characterisation of novel bacteriocins and antimicrobials. Traditionally large microbial screening studies were performed against a range of target organisms to identify *in vitro* antimicrobial activity. As genomic sequencing has become more affordable and prevalent, current antimicrobial screens can take an *in silico*-based approach using genomic searches. These genomic screening methods allow for a much more targeted approach for the identification of new antimicrobials. It is much less labour intensive compared to traditional colony screening, with a much higher success rate. The issue with genomic screening, however, is that these homology-based searches depend on the sequences of previously characterised antimicrobials, meaning that novel classes of antimicrobials may be overlooked due to their lack of similarity to previously characterised genes. Also, antimicrobials identified in large *in silico* screens are often not produced when tested *in vitro*, which can result a failure to characterise these potentially useful molecules. Here, we utilised both *in silico* and *in vitro* approaches for the identification and characterisation of bacteriocins and discuss their benefits and drawbacks.

In Chapter 2, traditional colony-based screening was used to isolate an antimicrobial-producing strain, *Bacillus paralicheniformis* APC1576. A wide number of colonies were initially isolated from the intestine of marine fish, which were then screened against a *Lactobacillus bulgaricus* strain to identify antimicrobial production. The fact that only one strain out of the thousands screened was identified as producing a novel bacteriocin demonstrates the low success rate of colony-based screening. Once this strain was identified as producing a novel antimicrobial, genomic sequencing of the strain was still required to identify the bacteriocin produced, formicin. Due to the high level conservation seen amongst the class of two-peptide lantibiotics, the bacteriocin genomic screening tool BAGEL easily identified this novel bacteriocin (de Jong et al., 2010). This study shows how traditional screening methods still have a place for the identification of novel antimicrobials, however, the combination of these methods with *in silico* screening provides a more elegant solution.

In Chapter 3 we adopted this targeted approach, using the genomic data of strains composing the *Lactobacillus* Genus Complex to screen for new bacteriocins and bacteriolysins. The BAGEL screening tool was used for the identification of bacteriocins encoded within the genomes of these strains (de Jong et al., 2010). Many of these strains have been long investigated for bacteriocin production, often due to their association with food preservation. Through *in silico* screening, this study provided an excellent overview of the genetic capacity of these strains to produce bacteriocins. We combined this with functional screening for antimicrobial production against a range of indicator organisms, this resulted in the identification of five novel bacteriocins. While these bacteriocins require further study and characterisation, some do offer potential industrial uses. Paralimenterocin, for example, can inhibit the growth of certain enterococci, and as the encoding strain was initially isolated from kimchii, it may have a protective role as a starter culture in the fermentation of vegetables. The combination of the initial genomic screen followed by the functional screen greatly increased the success rate in the identification of these novel bacteriocins. This approach is more efficient method for identifying new antimicrobials, cutting down the number of cultures to be screened through initial genomic homology-based searches.

In Chapter 4, we attempted overcome one of the main hurdles associated with genomic-based screening, which is the failure of many strains to produce the bacteriocins encoded within their genomes. Bacteriocin synthesis can be an energetically costly task for many bacteria, thus their production is often under tight regulation by the encoding strain (Uzelac et al., 2015). In the case of several of the bacteriocins identified here however, many key genes required for the synthesis and transport of the peptides were missing from the bacteriocin operon. To overcome the inability of such strains to produce a bacteriocin we used a heterologous expression system in which the pediocin PA-1 ABC transporter was cloned alongside a range of novel pediocin-like bacteriocins. We were able take advantage of the high degree of homology within this pediocin-like bacteriocin subclass. Of the novel class IIa bacteriocins identified from the *Lactobacillus* Genus Complex, their relatively high degree of homology to the bacteriocin pediocin PA-1 means that the pediocin-

associated transporter has the ability to secrete these new bacteriocins from the cells. Whilst this system works well for the class IIa bacteriocins, further work is required to determine the effectiveness of such an approach using different classes of bacteriocins. The study does show, however, how the *in silico* identification of novel antimicrobials can be translated into biological production using the correct expression systems. The benefits of this approach are shown in the fact that some of these class IIa bacteriocins expressed heterologously display a greater range of antimicrobial activity compared to pediocin PA-1, a commercially used bacteriocin.

A microbiome-based approach was used in Chapter 5 for the characterisation of microbial communities found in the intestinal tracts of deep-sea fish, as well as identifying their potential ability for the production of secondary metabolites. Whilst the production of antimicrobials is one mechanism by which microbes can influence the microbiome, often it is larger scale environmental changes which control which species occupy any given niche. This is seen with the potential identification of a link between the diet of the host and the metabolic capabilities of the microbes they harbour within their gut. The screen for genes related to the production of secondary metabolites shows the potential diversity of natural products which may be synthesised in the microbiome of these fish. Given how these bacteria display such adaptations to their environment, their apparent lack of resistance towards common antibiotics suggests that any natural products encoded within these communities may be highly novel. Studies such as this, however, need to be followed up with the heterologous expression of the identified operons, or the isolation of microbes from the source which can then be screened for *in vitro* antimicrobial production.

Taken together, this thesis outlines several approaches which can be used for the identification of novel antimicrobials. Reliance solely on either traditional or *in silico* screening methods limits the possibility of a successful outcome. Traditional wet lab screening is made much more efficient when combined with initial genomic screens, the only downside of which is the potential oversight of completely novel compounds due to the reliance on homology-based searches. *In silico* screening, if

not followed up by the expression and characterisation of the antimicrobial produced, offers little benefit when trying to develop new therapies targeting antibiotic resistant microbes. We show that when combined correctly, these approaches can lead to the identification of a range of new antimicrobials so that the full antimicrobial capability of the strains can be fully harnessed.

References

- BURKI, T. 2017. Antibiotic development pipeline slows to a trickle. *The Lancet Infectious Diseases*, 17, 1128-1129.
- CORR, S. C., LI, Y., RIEDEL, C. U., O'TOOLE, P. W., HILL, C. & GAHAN, C. G. 2007. Bacteriocin production as a mechanism for the antiinfective activity of *Lactobacillus salivarius* UCC118. *Proc Natl Acad Sci U S A*, 104, 7617-21.
- COTTER, P. D., HILL, C. & ROSS, R. P. 2005. Bacteriocins: developing innate immunity for food. *Nature Reviews Microbiology*, 3, 777-88.
- COTTER, P. D., ROSS, R. P. & HILL, C. 2013. Bacteriocins - a viable alternative to antibiotics? *Nature Reviews Microbiology*, 11, 95-105.
- DE JONG, A., VAN HEEL, A. J., KOK, J. & KUIPERS, O. P. 2010. BAGEL2: mining for bacteriocins in genomic data. *Nucleic Acids Research*, 38, W647-51.
- REA, M. C., DOBSON, A., O'SULLIVAN, O., CRISPIE, F., FOUHY, F., COTTER, P. D., SHANAHAN, F., KIELY, B., HILL, C. & ROSS, R. P. 2011. Effect of broad- and narrow-spectrum antimicrobials on *Clostridium difficile* and microbial diversity in a model of the distal colon. *Proc Natl Acad Sci U S A*, 108 Suppl 1, 4639-44.
- RHEE, S. J., LEE, J.-E. & LEE, C.-H. Importance of lactic acid bacteria in Asian fermented foods. Microbial Cell Factories, 2011. BioMed Central, S5.
- ROSS, R. P., MORGAN, S. & HILL, C. 2002. Preservation and fermentation: past, present and future. *International journal of food microbiology*, 79, 3-16.
- UZELAC, G., MILJKOVIC, M., LOZO, J., RADULOVIC, Z., TOSIC, N. & KOJIC, M. 2015. Expression of bacteriocin LsbB is dependent on a transcription terminator. *Microbiological research*, 179, 45-53.
- YOUNES, M., AGGETT, P., AGUILAR, F., CREBELLI, R., DUSEMUND, B., FILIPIČ, M., FRUTOS, M. J., GALTIER, P., GUNDERT-REMY, U. & KUHNLE, G. G. 2017. Safety of nisin (E 234) as a food additive in the light of new toxicological data and the proposed extension of use. *EFSA Journal*, 15.

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